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PROCEEDINGS OF THE PRAIRIE DROUGHT WORKSHOP

COMPTES RENDU DE L'ATELIER SUR LA SECHERESSE

Saskatoon, Saskatchewan
October 11-13, 1988 / le 11-13 octobre, 1988

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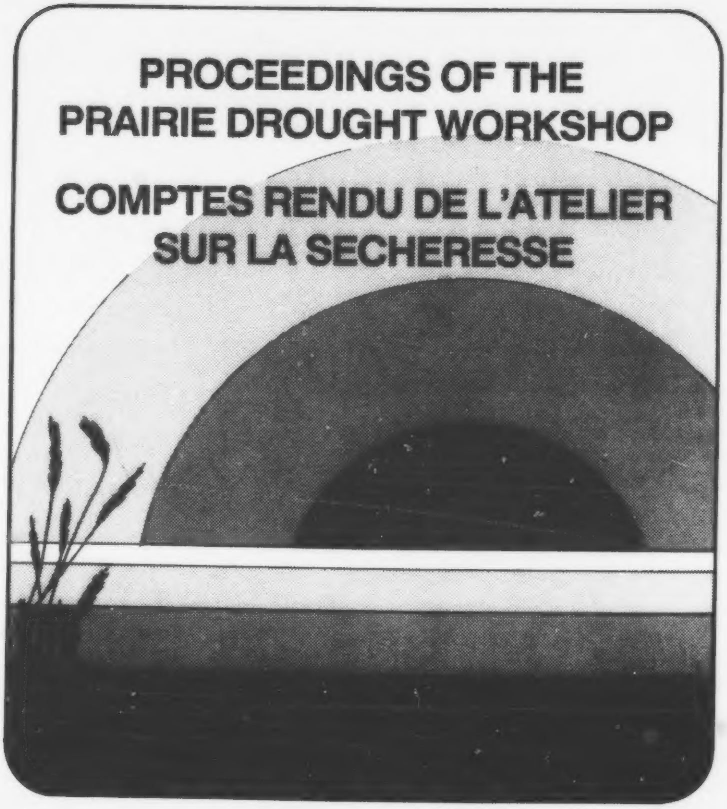

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PREFACE

The Prairie Drought Workshop was a collaborative initiative of the Hydrometeorological Research Division of the Canadian Climate Centre (CCC), the Hydrology Division of the National Hydrology Research Institute (NHRI) and the Prairie Farm Rehabilitation Administration (PFRA). Each of these three agencies contributed funds and provided expertise to assist in planning the workshop. The Program Office of the Canadian Climate Centre also provided funding support. Although the drought-related interests of these agencies are varied, this workshop succeeded in covering many of them. In particular, it focused on the physical processes which cause droughts, drought monitoring and prediction and the effects of climatic change on drought.

Drought is an important scientific issue for the Hydrometeorological Research Division of the CCC. In the past two years the Division has undertaken studies of the statistical properties of drought events in the Saskatchewan portion of the South Saskatchewan River Basin, a review of methodologies for drought prediction and a study of the meteorological conditions which accompany dry months in the different parts of the southern Canadian prairies. For this reason drought seemed like an appropriate topic to be addressed at the Division's annual workshop.

Drought is also a major research issue for the Hydrology Division of the National Hydrology Research Institute. This Division is concerned with research related to water management and is studying ways in which the scarce precipitation which falls during the winter months on the Canadian prairies can be retained and utilized by farmers during the spring. PFRA monitors drought and its impacts every year as appropriate. It is also responsible for putting programs in place which assist the farming community in alleviating the impacts of drought.

Some of the interest in the workshop can be attributed to the climate of 1988. The continuing dry conditions in the spring and summer heightened concerns about drought. The excellent presentations by the keynote and invited speakers and the focused workshop discussions led to a very productive workshop. An important element of the workshop's success was the planning team. Members of this team included Messrs Les Welsh and Don Bauer of the Hydrometeorological Research Division (CCC), Dr. Wally Nicholaichuk of NHRI and Messrs. Ted O'Brien and Walter Nemanishen of PFRA. Mr. Don Bauer is also commended for his efforts in preparing these proceedings.

This report is intended to serve as a basis for further research on drought. Information generated at the workshop is being incorporated into a framework for drought studies and into a proposal for a drought research unit. An action plan is also being developed to follow-up on the recommendations in this report. Those who read the report and would like to contribute to this follow-up are encouraged to contact the undersigned.

R. G. Lawford
Chief, Hydrometeorological
Research Division

ACKNOWLEDGMENTS

The Organizing Committee gratefully acknowledges the assistance of the many individuals who contributed to the success of the workshop. We thank all the keynote and invited speakers for their presentations and for providing manuscripts for inclusion in these Proceedings. We also thank the authors of the poster papers for their contribution to the workshop and for the material they have provided for the Proceedings.

The assistance of session and working group chairmen and rapporteurs helped ensure a successful workshop. We are also grateful to all those who assisted with the technical and social arrangements. We thank Dr. M. Dick, Director of the NHRC, for making the facilities of the Centre available for the workshop.

Lastly, we wish to thank Dr. E. F. Roots for chairing the workshop in his usual capable manner. His timely comments and astute observations did much to contribute to the success of the workshop.

Organizing Committee

L. E. Welsh (Chairman) D. J. Bauer

Hydrometeorological Research Division
Canadian Climate Centre
Saskatoon,Saskatchewan

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EXECUTIVE SUMMARY

Eighty-eight scientists and managers from Canada and the United States participated in a Prairie Drought Workshop held at the National Hydrology Research Centre in Saskatoon, Saskatchewan October 11 to 13, 1988. The workshop was sponsored jointly by the Prairie Farm Rehabilitation Administration (PFRA) of Agriculture Canada, and the National Hydrology Research Institute and the Canadian Climate Centre (CCC), both of Environment Canada.

The Workshop objectives were:

i) To transfer knowledge and technologies arising from drought research to users;
ii) To review new knowledge and research needs arising since the PFRA-CCC sponsored workshop held in Regina in 1983; the Canadian Hydrology Symposium No. 16-1986 held in Regina; and the Planning for Drought Workshop held at Lincoln, Nebraska in 1986; and
iii) To provide a forum for identifying research needs; reviewing research methodologies; and identifying opportunities for collaboration in research efforts.

The workshop consisted of four sessions each introduced by a keynote speaker and one or two invited speakers. Following the presentations the participants divided into working groups to deliberate over questions relating to the session topic and to formulate recommendations. There were also a number of Poster Papers on display during the workshop.

Mr. R. B. Godwin, former Executive Director of the Prairie Provinces Water Board and now a private consultant, set the tone for the workshop by giving a summary of the Canadian Hydrology Symposium No. 16-1986 and leaving the group with eight recommendations emanating from that symposium. His presentation was followed by the first of four scientific sessions.

Session 1, "Drought Driving Forces", addressed topics such as the role of stochastic processes, internal dynamics of the atmosphere and external influences in the evolution of drought. Questions relating to the role of ENSO, teleconnections and cyclical forcing (sunspots, etc.) in Prairie droughts were discussed in the working groups. We concluded that we do not yet have an adequate understanding of the role of the various drought driving forces and, therefore, require increased research into the interactions between land, sea and atmospheric processes. At the same time we should continue investigating possible external drought driving forces.

The keynote speaker for session 2, "Drought Monitoring, Detection and Early Warning", Jim Laver, focussed on drought monitoring activities in the United States and in particular on the production of NOAA's "Drought Advisories". Drought monitoring activities on the Canadian Prairies were outlined by the invited speakers. In this session working groups dealt with questions relating to drought definition, characterization, and geographic progression. It was agreed that a "holistic" definition of drought would be desirable, but likely not achievable, and thus a satisfactory definition of meteorological drought should be developed as the primary indicator of drought. Participants felt that, except for soil moisture, most drought monitoring networks were adequate, however, they expressed concern over the lack of standardization of data and identified a need to improve the access to and communication of meteorological and hydrological data.

As a result of the presentations and discussions in session 3, "Drought Prediction", the participants concluded that as yet we do not have the capability to predict meteorological droughts. There is some degree of skill in predicting anomalies (especially temperature) over a one-month period and the outlook for seasonal predictions is encouraging. It was felt that better Numerical Weather Prediction models will be required to develop improved long-range forecasts. Participants expressed concern that many users lacked information about and understanding of long-range atmospheric predictions.

The final session focused on "Drought in the Future". The keynote speaker expressed the view that although scientific modelling of the Greenhouse Effect still has a large measure of uncertainty about it, the hypothesis of a global warming of several degrees is plausible. Therefore, planning for future water resources management and agricultural practices should attempt to improve the ability to cope with drought, higher temperatures and altered seasonality of precipitation. While it was felt that drought severity might increase with a warming trend, there was no consensus that drought frequency would increase in the future. It was agreed that drought planning and studies of the socioeconomic consequences of drought should be a priority regardless of projected climatic change. The interdisciplinary aspects of drought research were emphasized along with a need for improvements in some of the monitoring networks.

The summary workshop recommendations are as follows:

Research:

1. Research into developing the physical/dynamical model approach to drought forecasting should be expanded. Such research should be interdisciplinary and must include interactions between sea and land processes and atmospheric dynamics as related to the

onset, termination and severity of droughts. At the same time, research should continue into developing statistical/empirical approaches to drought forecasting.

2. There should be increased support for theoretical studies into the causes of climatic warming (e.g. ENSO events, etc.) and for improvement to the hydrologic component of Global Circulation Models including the effect of man's influence (e.g. land-use changes). In particular research should be directed to improving the AES-CCC model so as to accurately forecast precipitation.

3. Research is needed to identify the processes which initiate and terminate a drought and to assess the relative importance of each of these processes. In addition to studying physical/ dynamical and stochastic processes the role of anthroprogenic factors should be examined and evaluated. Paleoclimatological data and ocean sediment cores should be used to extend the record available for studying sea surface temperatures and prairie drought.

4. Meteorological droughts should be quantified with respect to their spatial and temporal distributions and their intensities. The linkages between meteorological droughts and other "drought types" need to be defined.

Public Education:

1. The Atmospheric Environment Service should take the lead in educating users and potential users as to the validity, utility and application of long-range atmospheric forecast products .

2. Public acceptance of the potential for climatic warming and the resultant consequences is needed and for this we need public understanding and awareness.

Policy:

1. Drought planning should be given more focus, regardless of projected climatic change. The federal and provincial governments should formulate and implement an integrated and sustained program for coherent investigation of promising drought mitigation measures, concentrating especially on the Palliser Triangle area. In order to achieve this a better understanding of the long-term effects of drought mitigation policies on land management is required.

2. Even though we lack a full understanding of drought causes, and are a long way from reliable drought prediction, socio-economic impact questions related to climatic variability must be addressed. Such impact studies should distinguish between single and sequential droughts and should investigate the "ripple"

effect through the economy. Model response functions based on previous droughts and regional aspects of drought should be used to develop an integrated, regionally based land policy.

Monitoring:

1. On the expectation that any anthropogenically caused climate warming trend will be most pronounced in northern latitudes we should undertake increased monitoring (including downward long wave radiation and soil moisture field monitoring) over Canada to detect climatic trend signals.

2. There is a need for standardization, among the many agencies involved, of data gathering and dissemination. It is recommended that a multi-agency data management plan be devised which includes network design and standardization, data quality, inadequacies in existing networks, supplemental networks, remotely sensed data, automation and data communication and access.

3. There is a need for a common definition of drought. A holistic drought index would be ideal, but in view of the difficulties in developing such an index it is recommended that the primary drought index used be for a meteorological drought. Such an index should quantify meteorological droughts according to extent (temporal and spatial), intensity and timing (beginning and ending) and in some way take into account the effect of multi-year droughts. Based on this index of meteorological drought linkages between meteorological drought and other types of drought should be defined.

The Prairie Drought Workshop provided an excellent forum to review and share our current knowledge of drought, identify research needs and potential areas for collaborative research. We were reminded that we must accept the fact that periods of drought are a part of the climate of the Canadian prairies (and indeed all of the Prairies) and may possibly become more frequent in the future. We concluded that at present we cannot yet satisfactorily predict the occurrence and severity of prairie droughts and increased research into the causes, specification and prediction of drought is required. We also discovered that the socio-economic impacts of drought and drought mitigation programs are not well understood and need to be thoroughly investigated.

D. J. Bauer
Editor

SOMMAIRE

Quatre-vingt-huit scientifiques et gestionnaires du Canada et des États-Unis ont participé à un atelier sur la sécheresse des Prairies qui s'est tenu au Centre national de recherches hydrologiques de Saskatoon (Saskatchewan) du 11 au 13 octobre 1988. L'atelier était parrainé par l'Administration sur le rétablissement agricole des Prairies (ARAP) qui relève d'Agriculture Canada et par l'Institut national de recherches hydrologiques et le centre canadien climatique (CCC) qui relèvent d'Environnement Canada.

Voici les objectifs de l'atelier :

i) Transférer les connaissances et les techniques provenant des recherches sur la sécheresse;

ii) Revoir les nouveaux besoins en connaissances et en recherches qui ont été créés depuis l'atelier parrainé par l'ARAP et le CCC qui s'est tenu à Regina en 1983, le Colloque canadien sur l'hydrologie n° 16-1986 qui s'est tenu à Regina; et la Planification d'un atelier sur la sécheresse qui s'est tenu à Lincoln, au Nebraska, en 1986; et

iii) Prévoir un débat ouvert pour préciser les besoins en recherche; revoir les méthodes de recherche; et préciser les possibilités de collaborer dans le domaine des recherches.

L'atelier comportait quatre séances, chacune ouverte par un conférencier principal et un ou deux conférenciers invités. Après la présentation de l'exposé, les participants se sont réunis en groupes de travail pour débattre les questions ayant fait l'objet de la séance et pour formuler les recommandations. Un certain nombre de documents ont aussi été exposés durant l'atelier.

M. R.B. Godwin, précédemment directeur exécutif de la Régie des eaux des provinces des Prairies et à l'heure actuelle un expert-conseil du secteur privé, a ouvert l'atelier en présentant un sommaire du Colloque canadien sur l'hydrologie n° 16-1986 et en communiquant au groupe huit recommandations qui découlaient de ce même colloque. Son exposé a été suivi par la première des quatre séances scientifiques.

La première séance sur les "forces menant à la sécheresse" s'est attaquée à plusieurs sujets, à savoir : le rôle du processus stochastique, la dynamique interne de l'atmosphère et les influences externes sur l'évolution de la sécheresse. Les groupes de travail ont discuté des questions liées au rôle de l'ENSO, des téléconnections et des forces cycliques (taches solaires, etc.) dans les sécheresses des Prairies. Nous avons conclu que nous n'avons pas encore une compréhension suffisante du rôle des diverses forces menant à la sécheresse et que, par conséquent, il était nécessaire d'approfondir les recherches sur les interactions des processus terrestres, maritimes et atmosphériques. En même temps, nous devrions continuer d'enquêter sur les forces externes probables menant à la sécheresse.

Le conférencier principal de la deuxième séance portant sur "la surveillance, la détection et l'avertissement précoce de la sécheresse", M. Jim Laver, a centré ses commentaires sur les activités de surveillance de la sécheresse aux États-Unis et en particulier sur la production des "Drought Advisories" de NOAA. Les conférenciers invités ont exposé les activités de surveillance de la sécheresse dans les Prairies canadiennes. Au cours de cette séance, les groupes de travail ont traité de questions liées à la définition, la caractérisation et la progression géographique de la sécheresse. On s'est montré d'accord pour dire qu'une définition "holistique" de la sécheresse était souhaitable, mais probablement pas réalisable, et qu'on devrait donc en venir à une définition satisfaisante de la sécheresse météorologique comme indice primaire de la sécheresse. Les participants ont estimé que, à l'exception de l'humidité, la plupart des réseaux de surveillance de la sécheresse étaient adéquats; néanmoins, ils se sont inquiétés du manque de normalisation des données et ont fait ressortir la nécessité d'améliorer l'accès aux données météorologiques et hydrologiques, y compris la transmission de ces mêmes données.

Comme suite aux exposés et aux discussions de la troisième séance portant sur la "prédiction de la sécheresse", les participants ont conclu qu'ils n'avaient pas, jusqu'à présent, la capacité de prédire des sécheresses météorologiques. Prédire des anomalies (particulièrement la température) sur une période d'un mois demande un certain talent, sauf que la perspective des prédictions saisonnières est encourageante. On était d'avis qu'il fallait de meilleurs modèles de prédictions météorologiques numériques pour élaborer de meilleurs prévisions à long terme. Les participants se sont inquiétés de ce que de nombreux usagers n'avaient pas de renseignements au sujet des prédictions atmosphériques à long terme, ni ne comprenaient cette question.

La dernière séance a été axée sur la "sécheresse à l'avenir". Le conférencier a exprimé l'opinion que, bien que l'expression scientifique d'un modèle de l'effet de serre comporte toujours en lui-même un haut degré d'incertitude, une hypothèse d'un réchauffement global de plusieurs degrés est néanmoins plausible. Par conséquent, les plans de gestion des ressources en eau et des pratiques agricoles de l'avenir devraient essayer de rehausser l'aptitude à faire face à la sécheresse, aux températures plus élevées et à la saisonnalité modifiée de la précipitation. Bien qu'on soit d'avis que la gravité de la sécheresse pourrait s'accroître parallèlement à une tendance de réchauffement, il n'y avait pas de consensus parmi les participants sur l'accroissement de la fréquence de la sécheresse à l'avenir. Il a été convenu que la planification de la sécheresse et les études des conséquences socio-économiques de la sécheresse devraient constituer une priorité, peu importe les projections concernant les changements climatiques. Les participants ont insisté sur les aspects interdisciplinaires des recherches en sécheresse ainsi que sur la nécessité d'améliorer certains des réseaux de surveillance.

En bref, voici les recommandations de l'atelier :

Recherche :

1. Approfondir les recherches afin d'élaborer une approche par modèle physique et dynamique à la prédiction de la sécheresse. Ces recherches doivent être de nature interdisciplinaire et comprendre les interactions des processus terrestres et maritimes ainsi que la dynamique atmosphérique dans la mesure où ces aspects sont liés au déclenchement, à la cessation et à la gravité des sécheresses. En même temps, on devrait continuer de rechercher des moyens statistiques et empiriques pour prédire les cas de sécheresse.

2. Appuyer davantage les études théoriques portant sur les causes du réchauffement climatique (par exemple événements ENSO, etc.) et la tâche d'améliorer l'élément hydrologique des modèles de circulation globale, y compris l'effet de l'influence de la personne (par exemple : changement en matière d'utilisation des terres). En particulier, la recherche devrait être orientée sur l'amélioration du modèle SEA-CCC de manière à prédire exactement la précipitation.

3. Entamer des recherches pour identifier les éléments qui engendrent et mettent fin à une sécheresse et pour évaluer l'importance relative de chacun de ces éléments. En plus d'étudier le processus stochastique et dynamique-physique, il importe d'examiner et d'évaluer le rôle des facteurs anthroprogénétiques. Il faudrait recourir aux données paléoclimatologiques et aux sédiments de l'océan en vue d'augmenter les renseignements dont on dispose pour étudier les températures de la surface de la mer et la sécheresse des Prairies.

4. Quantifier les sécheresses météorologiques sur le plan des intensités et de leur répartition spatiale et temporale. Il faudrait aussi définir les liens entre les sécheresses météorologiques et les autres "genres de sécheresse".

Renseigner le public :

1. Le Service de l'environnement atmosphérique devrait être le premier a renseigner les utilisateurs ainsi que les utilisateurs probables sur la validité, l'utilité et l'application des moyens de prévisions atmosphériques à long terme.

2. L'acceptation du public de la possibilité d'un réchauffement et des conséquences est nécessaire et, à cette fin, il importe que le public comprenne la situation et y soit sensibilisé.

Politique :

1. Il faudrait réaccorder plus d'importance à la planification concernant la sécheresse, peu importe les changements climatiques prévus. Il appartient au gouvernement fédéral et provinciaux de formuler et d'appliquer un programme intégré et permanent permettant d'étudier de façon cohérente des mesures prometteuses pour alléger la sécheresse, en se concentrant spécialement sur la région du triangle Palliser. Afin d'atteindre cet objectif, il est nécessaire de mieux comprendre les effets

à long terme des politiques propres à l'allégement de la sécheresse sur la gestion des terres.

2. Bien que nous ne comprenions pas entièrement les causes de la sécheresse et que nous sommes encore loin d'une prédiction fiable, il importe de s'attaquer aux questions de l'impact socio-économique liées à la variabilité climatique. Ces études d'impact devraient établir une distinction entre les sécheresses uniques et séquentielles et étudier de façon plus approfondie l'effet de vague sur l'économie. Il faudrait aussi recourir aux fonctions de réaction du modèle basées sur les sécheresses précédentes et les aspects régionaux de la sécheresse pour élaborer une politique régionale intégrée propre aux terres.

Surveillance :

1. En prévision d'une tendance de réchauffement du climat attribuable à une cause d'ordre anthropogénétique, tendance qui sera la plus prononcée dans les latitudes septentrionales, nous devrions accroître notre surveillance (y compris la radiation des ondes longues descendantes et la surveillance sur place de l'humidité du sol) au-dessus du pays pour détecter des signaux de tendances climatiques.

2. Compte tenu de la participation de nombreux organismes, il faudrait normaliser la collecte et la diffusion des données. On recommande de dresser un plan de gestion des données qui comprendra la normalisation et le design du réseau, la qualité des données, les insuffisances des réseaux existants, les réseaux complémentaires, les données détectées au loin, l'automatisation et la transmission des données et l'accès aux données.

3. Il est nécessaire de bien définir la sécheresse. Un index de sécheresse holistique serait idéal; toutefois, compte tenu des difficultés à mettre au point ce genre d'index, il est recommandé d'utiliser l'index primaire pour une sécheresse météorologique. Cet index doit quantifier les sécheresse météorologiques conformément à l'étendue (temporale et spatiale), l'intensité et l'époque (le début et la fin) et tenir compte, de quelque façon, de l'effet des sécheresses pluriannuelles. En fonction de cet index de sécheresse météorologique, on pourrait définir les liens entre la sécheresse météorologique et les autres genres de sécheresse.

Cet atelier sur la sécheresse des Prairies a créé l'occasion d'un excellent débat ouvert permettant de revoir et de partager nos connaissances actuelles sur la sécheresse, de préciser les besoins en recherche et les domaines probables se prêtant à la recherche en collaboration. On nous a rappelé que nous devons accepter le fait que les périodes de sécheresse forment une partie intégrante du climat des Prairies canadiennes (et, en réalité, de toutes les Prairies) et qu'elles pourraient se produire plus souvent à l'avenir. Nous avons conclu, qu'à l'heure actuelle, nous ne pouvons pas encore prédire d'une façon satisfaisante le déclenchement et la gravité d'une sécheresse dans les Prairies et que nous devons intensifier les recherches sur les causes, les particularités et la prédiction de sécheresse. Nous avons aussi découvert qu'on ne comprend pas très bien les répercussions socio-économiques de la sécheresse ni les programmes d'allégement, et que ces questions doivent faire l'objet d'une étude approfondie.

PRAIRIE DROUGHT WORKSHOP

INTRODUCTION

DROUGHT WORKSHOP
Opening Remarks

THE STUDY OF DROUGHT:- SCIENTIFIC APPROACHES TO A HUMAN PROBLEM

E.F. Roots

1. INTRODUCTION

It is a great pleasure to be given a chance to take part in this workshop. The topic is timely and important, as we all know; - important not only for its local economic, social and political significance in the Prairies, but for what it means for our growing understanding of what is happening to the planet and the way we use its resources. I am sure that we will find a lot in common, and a lot that we will argue heatedly about as we compare and try to explain what we think we understand about these complex phenomena; - but I hope that even our arguments will bring us closer together.

2. THE OBJECTIVES OF THE WORKSHOP

You have seen in your package the formal objectives for the workshop. I think the overall objective can be appreciated by everyone - it is to examine current drought research and to find some way to transfer the knowledge and the technologies that have come out of that research to those who can benefit from the increased knowledge. Those who can benefit, called "users" on our programme leaflet, can range from government policy-makers to farmers to international wheat cartels, and, not least, will include Nature itself, the local and regional ecosystem. To work toward this objective we will want to review advances in research, appraise the new knowledge that comes from those advances, and from that perspective look at the application of this knowledge in the real world. We will also identify new research needs.

We want to discuss together the research priorities as we see them, and we will likely have quite different views on what those priorities will be. We will look at new research methodologies, welcome some, be critical of others; and see where they fit into our questions. And, importantly, we will look at opportunities for collaboration, and at all the obstacles to co-operation between scientists, between institutions, and between those who have to live with drought or predict its course, and the many people who have to make decisions in a drought situation.

3. BACKGROUND - PREVIOUS RELATED MEETINGS

As your program points out, this workshop follows a number of others in the last few years that have been held in the Prairie area on related subjects. The Workshop on Drought in 1983 in Regina, which was sponsored by the Canadian Climate Centre and the PFRA examined the state of knowledge, at that time, about the Prairie climate and reviewed ideas about how significant were the changes that were then being observed. That review, five years ago, is perhaps even more valuable today. Then there was the Canadian Hydrology Symposium in 1986, also in Regina, which focussed on what was called the "hydrology crisis", - much better, surely, just to call it a water availability crisis - how important was the immediate and the longer-term crisis at the time and how could it be dealt with. We will undoubtedly hear more about that symposium and its follow-up later this afternoon. Your program also mentions the Planning for Drought meeting in Lincoln, Nebraska, also in 1986, which looked at the institutional and organizational responses and economic implications of drought questions. Each of these meetings has dealt with research on Prairie drought, but from a different orientation.

There have been many other meetings on this general subject in recent years which are part of the background, I think, that many of us here bring to this meeting. These meetings range from local and topical planning and review discussions such as those connected with the Western Economic Opportunities Program which continued for a number of years, to international and global conferences. One of the objectives of the WEO meetings, if we remember, - I don't think we should blush to say it -, was to find ways to "drought-proof" the Prairies. There was an assumption, at least partly borne out by experience, that if money were made available, even if one could not make it rain, one could invest in advance and reduce the losses from lack of rain. On a broader scale, but also related to our topic, have been a large number of activities such as the United Nations Symposia on Arid Lands, symposia on the hydrology of areas of low precipitation, or the series of meetings in Villach Austria, 1985-1987 on climate change includinig considerations of the vulnerability of drought prone areas under changing climate, which were held under the auspices of the World Meteorological Organization and the United Nations Environment Programme. All of these scientific meetings dealing with water shortage and anomalous or changing climate in various scales have shown how complex are questions dealing with drought, how the issues are interrelated amongst many areas of interest and knowledge, and how they touch on many centres of responsibility. They also show how important the subject is, scientifically, socially and economically, and politically.

4. WHAT IS DROUGHT?

The question comes up immediately, "What is drought?". During the next two days, this question will be looked at anew from many angles; but I hope that at this workshop we don't get hung up on the problem of definition, or take too narrow a view of what we are talking about. We will hear at this workshop I am sure, terms such as meteorological drought, hydrological drought and agricultural drought, and so on. These terms are useful for certain concepts, but let us keep arguments about them to a minimum. You all have, I think, in your background information the excellent draft paper by Bruce Godwin, Gordon MacKay and John Maybank, which points out the imprecise nature of the general use of the term, and gives some definitions for "drought". In most dictionaries, drought is defined in terms of temporary and unusual dryness of a region. So it is a relative term; - how dry, for how long, compared to what, is the problem of definition and comparison, although there is rarely a problem of recognition of a drought when one is in the midst of one.

You will notice that the paper referred to says that droughts are natural phenomena whose occurence is certain. Of course they are. But no two droughts are the same. For our purposes at this workshop, where we are looking at research questions distinctive to the processes that give rise to drought and maintain it, to the atmospheric and environmental features that distinguish Prairie droughts, and to the improvement of the ability to predict the onset of droughts or their continuation once the condition of unusual dryness has set in, there are a few common characteristics that I think we all should agree upon; such agreement will be important as a starting point for our discussions. As I see it, the term "drought" as we will use it in this workshop will embody three principal ideas:-

(i) There is less moisture available to biological or industrial systems than has been normal in that particular region for the past few decades. There is thus an "unusualness" aspect;

(ii) The dryness happens for a long enough time to be important in natural or human terms but not long enough to establish a recognizable new climatic norm or a new environmental regime. Thus, drought as we view it has a "transient" aspect; it is often not as temporary or as rare as people would like, but any single drought does not necessarily indicate a new direction of climate variation;

(iii) Drought must be a departure from the norm that is great enough or sudden enough to affect human activities seriously but not permanently. There is therefore a human dimension of "short-term undesireability" that is important to the concept of drought.

These three elements of unusualness in the water deficiency, of a transience in the shortage, followed by an expected return to normality (whatever that is), and a negative effect on human activities or values are important for discussions on the priorities, accomplishments, and application of research on drought.

We all know that drought is not just absence of water. If an area completely or almost completely dries, it is no longer suffering from drought but it has become arid, and thus has entered a new climatic, physiographic and biological state. It is the relative absence, compared to what is expected or desired, that is important. One could note, for example the definition for drought used for water management decisions in the United Kingdom, which is 15 consecutive days without precipitation. Fifteen days without rain could signal a serious drought in the United Kingdom, which has, by world averages, lots of water; but in Death Valley, the year in which it rained twice, - that is, every 150 days - might be considered a wet year. So it is not the absolute amount of moisture or the frequency of precipitation that makes, or breaks, a drought. There is a difference between drought and an annual dry season, which is a normal condition for many parts of the world, especially in lower latitudes. Drought is a condition which is abnormal for a given region at a given time of year, not a condition drier than it generally is in some other region or at some other time of year.

The relation of actual precipitation to what humans want it to be at that time and place is another important aspect of drought. If you were the ancient mariner adrift on the ocean, trying to collect rain water to drink, and it doesn't rain for a long time - "Water, water everywhere, but not a drop to drink" -, you would be experiencing drought. But if you were on the same ocean on a sub-tropical holiday cruise and wanted to be sun-bathing all day every day, you may have paid good money on the chance that it won't rain, and the continuous sunshine is not drought, it's what you came for. I just point out these obvious situations as examples of the subjective and relative nature of the phenomena we are addressing. Drought in general is not a scientifically definable condition. It is a subjective condition of the natural environment whose processes, characteristics and consequences need careful scientific study.

5. DROUGHT RESEARCH

Like drought itself, drought research has many aspects, some very hard to define. The most obvious fields of study into the phenomena of abnormal temporary dryness will form the main threads of the presentations and discussions at this workshop, but if we have the right mixture of people here - and I am sure that we have - and if we do our job properly, we will be involving in our discussions a wide range of investigations in many fields of science and environmental assessment. Drought research must start with climate studies, of course; for it is the character of the climate and the behaviour of the weather that gives rise to the conditions that result in drought. Thus, questions of the patterns of precipitation as well as the amount, and the factors that cause and control changes in the patterns, are crucial to drought research.

Drought is clearly a hydrological as well as a climatic phenomenon. At a workshop on drought held at the National Hydrological Research Institute it is scarcely necessary to point out the role of investigations into the relationships and controls of the aerial, the surficial (including biological) and the underground parts of the hydrological cycle as essential components of drought research. Perhaps we will find that we need to pay particular attention to the hydrological processes and controls that operate on relatively small space and time scales, as well as on regional and global or multi-year scales, to understand the hydrological aspects of drought.

Questions of the energetics of moisture transfer, horizontally and vertically, within the atmosphere, between the atmosphere and the earth's surface including its organic and soil or water surfaces, and within the soil are obviously important to the maintenance and consequences of drought. The chemical aspects of atmospheric, hydrological and pedological, and biological interactions related to droughts are less obvious - or perhaps have received less study -, but the preliminary findings from recent climate change research suggest that subtle changes in climatic chemistry may be very important factors in the occurrence and persistence of droughts.

In droughts affecting the northern North American prairies, snow and ice play a rather distinctive role - a role that is not present or is minor in many parts of the world where drought affects large numbers of humans. Thus, Canadian drought research must include careful studies of the physical, biological and chemical aspects of ice and snow, and of phase change, in determining not only the pre-conditions and characteristics of drought, but the environmental consequences and the practical measures that can be taken to cope with its effects.

Research in the soil sciences is quite obviously a central component of drought research. Soil science, like environmental sciences, can mean many things to many people; but the response to a shortage of water of the geological, hydrological, cryological, geochemical and biological processes that create and maintain our soils, and the effect of the elevated temperature gradients in the upper few centimeters that are characteristic of most soils experiencing drought, are essential areas of research. So are the effects on soil texture, percolation, runoff, etc. of any treatments or cultivation practices that may be applied to mitigate the effects of drought.

A further dimension of drought research must deal with the responses of the ecosystem to periods, or seasons, of unusual regional dryness. In the Prairies, the natural ecosystem has evolved under conditions of occasional or periodic drought. The natural response of most of the higher plants or animals appears to be, not surprisingly, lower productivity or local die-off; but some soil bacteria, parasites, and other creatures appear to have at least a temporary comparative advantage in times of drought. The human-managed agricultural ecosystem, however, does not easily accept periods of low productivity and local die-off. Care must be taken to ensure that measures taken to maintain productivity during unusual dry periods do not become counter-productive by decreasing the long-term natural productivity of soils, crops and livestock, and increasing the vulnerability to future changes. Research into the consequences of drought and how to deal with them must include studies of the behaviour and responses of both natural ecosystems and human-managed biosystems in drought-prone areas; and those studies in turn must be related to climatological, hydrological and soil sciences research.

Another important area of drought-related research, related to those noted already but quite different in its approach and the disciplines that must be employed, is that of the effect of drought on human behaviour and institutions. Some of the obvious effects that the Prairie droughts of the 1930's, or in the spring of 1988, had on the local and regional economy, employment, market structure, transportation and related services, etc., are well known in general terms; but it seems that there has been little careful research into the linkages between the climatic and biological phenomena that characterize the drought and the human or institutional responses. What specific features of the environmental or agricultural anomaly, over what scale and at what severity, led to what human actions? What aspects of financial institutions took precautionary actions, according to what signals or criteria; and what aspects of government at what level were best able, or were unable, to respond? Who paid first for the damages and dislocation caused by drought, and how? Who ultimately paid, and how was the "bill" spread to the nation? Did anyone benefit substantially from the drought? Did the drought have an effect of triggering or shaking up institutions or attitudes that were outmoded and needed to be changed anyway? These are all questions open to research in the economic, behavioural and political sciences - research for which much evidence and data are at hand, and which should be used or followed up before it is lost or dissipated. Just as no two droughts are the same, certainly the human and institutional response to any drought will never be twice the same. But if we are to learn more about the natural causes and effects of drought, with the hope of perhaps being better able eventually to predict them and their effects, we need also to do careful research on the behavioural, institutional, and economic/political aspects of drought response, so as to put our scientific knowledge to better human and institutional use.

If you look through the programme for this workshop and the Working Group discussions, you will see ample opportunity and encouragement to consider all these areas of drought research, and their inter-relationships.

6. CHANGES OF KNOWLEDGE AND AWARENESS

This workshop is being held at a time when there have been many recent advances in the understanding of the workings of the planet Earth, and growth of awareness of the effect of humans on the processes and resources of the Earth. Among the most important new knowledge is that related to climate and hydrological systems, key subject areas in the study of drought. Even compared to the situation of a couple of years ago, there is today, thanks to the studies related to the World Climate Research Programme, the World Ocean Climate Experiment, the research reviews in preparation for the International Geosphere-Biosphere (Global Change) Programme, the Man and the Biosphere Programme and the International Hydrological Programme of UNESCO and many other fundamental and applied international studies, a much better scientific understanding of the inter-correctedness of processes that link the biological, geophysical and chemical worlds, and the effects of human activities on them. From this increased scientific understanding is emerging a better awareness, not only by scientists but by policy-makers and the public - particularly that part of the public that makes its living directly from the land - of the relationships between natural events that are involved in unusual occurrences such as droughts.

The increasing scientific understanding gives us a basis for a new synthetic approach to the study of drought, rather than the analytical approach that was characteristic of most studies in the past few decades. Elements of a synthetic research approach are:

- a focus on the interactions between the biological, geophysical and chemical processes that determine environmental characteristics;

- an increased ability to put into perspective the wide range of time scales and space scales of the reactions that link local processes to the global system. Such a perspective helps to show that temporary or transient phenomena, such as droughts, are both triggers for and manifestations of longer-term and larger-scale environmental dynamics. When looked at in this perspective, it is difficult or meaningless to study any temporary variation in environmental events - such as a prairie drought, or an El Nino - without relating it to larger causes and consequences;

- an increased awareness of the natural instabilities of the processes that maintain the present environment and the rapidity, sometimes the irreversibility, of the response of soils and hydrological systems to changes in climate;

- a better appreciation of the effects of human activity on the different workings of the "natural" environment; - of the role of humans in factors leading to climate change; and, all too often, in exacerbating the undesired biological effects of such changes, often with tragic results. We need only to look at the land erosion from new tillage practices in Ethiopia and the resultant famine, or the effect of tree-cutting in the sub-arid borderland of the Sahel to see how human activities can intensify the human consequences of drought. Closer to home, we will want to bring all the scientific knowledge we can muster to bear on the relationship between tillage practices, crop planning, climatic factors, drainage schemes and loss of topsoil during drought in Saskatchewan.

Along with new scientific understanding, there are at our disposal new tools for research, which certainly were not available for study of the droughts of the 'thirties, and which even today are not fully used for environmental research. These include the use of simulation models, well-developed in climate research and coming into use in hydrological sciences, but not yet a common part of biological studies, although the Man and the Biosphere Programme and the

Global Change programmes are addressing the potential of integrated modelling. Games theory and the explorations into organization of random events would appear to be well suited to studies of droughts, but I am not aware that they have been applied to help determine the critical factors that initiate, or end, a drought condition. Similarly, the subject of risk analysis is advancing rapidly, and promises to be helpful toward making the operational and policy decisions associated with management of human affairs during and following periods of drought. Most of these new tools require a good deal of data; but on the Prairies at least the data are improving in quantity and quality, through satellite observations, better hydrological reporting networks, and better organization of data banks.

7. TIMELINESS, - AND THE NEED FOR SCIENTIFIC AND HISTORICAL PERSPECTIVE

This is a very propitious and rewarding time to be discussing the progress and the challenges of drought research. Of course, the subject is timely and of extreme importance. In North America, we are acutely aware of the Prairie spring dryness of the last three years, culminating in this year's drought; and of the moisture deficiency in the soils as we look forward to next year. On a larger scale, there is the desertification in the Sahel, Ethiopia and Sudan and all its social, economic and political consequences; the "danger-level" dryness of the northern Mediterranean and Black Sea region; the speculations of long-lasting regional moisture deficiencies associated with global warming in which food-producing areas occasionally plagued by drought may turn into arid areas producing almost no food. All these make a workshop on this subject, at this time, most important from a management or policy as well as from a scientific point of view.

But at the same time, when addressing the issues of prairie drought, we shouldn't get too carried away with today's short-term concerns, or come to feel that our study of it was new. Drought is as old as agriculture, and six thousand years ago, in ancient Ur, rivers were diverted to provide additional water during times of drought. In 1857-60 Dr. James Hector, one of Canada's most perceptive, but little appreciated early scientific observers, a member of the Palliser expedition, wrote after travelling across what is now Saskatchewan a little south of here, "from the character of the soil and the vegetation, the country appears to be subjected in some years to periods of extreme dryness". (Hector, 1861). The Palliser expedition went across the prairies not in a dry year, but Hector recognized the signs of periodic drought. Very often we have ignored the value of some of those careful early observations and what they can teach us about the dynamic environment of the Prairies and their management. We tend to over-simplify by talking about the "Palliser triangle", and remembering Palliser's recommendation that the water-deficient area would not be as suitable for agricultural development and investment as the surrounding parts of the Prairies. But Hector recognized that the "fertile area" would also be prone to periodic drought. And I think we should ask ourselves - can we give better advice today than Hector and Palliser gave in 1861? Certainly, we know more about the causes and extent of the phenomena that they observed, and the social and economic consequences both of prosperous development and of drought are greater and more far-reaching than they could ever have imagined. But with all the data and forecasting tools at our disposal, can we really make a better analysis and give better advice?

8. AREAS NEEDING RESEARCH ATTENTION

Before we get too enmeshed in technical presentations and workshop sessions, it may be useful to think, in non-technical layman's language, what aspects of this whole complex subject are most in need of new or better scientific knowledge, and thus are most in need of research attention. From my own watching of some of the activities related to drought, its causes and consequences and what might be done about it, I will leave with you some suggestions of areas where it seems to me we need to put some resources and imagination into research in the next decade. These suggestions are not in order of priority nor of comparable magnitude, and are not separate from one another; they are listed just to get us thinking together that both our sophisticated science and our common-sense experience need to be harnessed to address the issues of drought. I hope the following areas will be developed further, or rejected as not important, at this workshop:-

- the relationship between local and regional manifestations of climate change. (How to relate Global Circulation models to what happens in the Q'Appelle Valley?);
- the historical sequences, characteristics, and areas affected by prairie drought, especially the sequences of happenings in the season following the end of the drought (requires meteorological, hydrological, sedimentological and biological information);
- the sequence of events and processes that are precursors of drought, trigger its onset (if it is "triggered") and maintain it (requires study, analysis and synthesis of events upwind, to each side, and downwind);
- the relationship between precipitation, runoff, groundwater storage and flow for a range of precipitation volumes (is our hydrology and perhaps our hydrogeochemistry good enough to enable modelling of the same soil from flood to near-dessication?);
- the effects on the quality of surface waters and groundwaters of drought, semi-drought, and return to normal water levels (hydrogeochemistry and soil microbiology);
- the response of a prairie ecosystem that is already stressed by climate changes, acid rain, etc., to different intensities of prairie drought;
- the physical, chemical and ecological processes and sequences in the recovery from drought;
- the incorporation of drought risks into regional development and economic planning (what would be done differently if there were adequate warming - a month in advance? six months in advance?);
- mechanisms and methodologies for (i) controlling human activities that may contribute to the onset and maintenance of drought; (ii) mitigating some of the most severe environmental or socio-economic effects of drought and the post-drought "recovery".

All this (and the list could be much extended) is an enormous task, to learn about an enormous subject. But if you look through your workshop agenda and the subjects of the main papers, these subjects, and more, are what we are here to explore.

9. THE WORKSHOP

As Mr. Lawford mentioned, and you can see from the programme, the workshop is structured in four sessions. Each session has a chairperson who I will be introducing as the meeting progresses. Each session chairperson will introduce a keynote or an invited speaker. After the presented papers we will break into workshop sessions, and at the end of each session there will be a brief summary by the session chairperson. I want to draw your attention also to the poster papers, one in this room and the rest are down the hall. I urge you to find the time, even if you have to cut short your wine and cheese this evening, to study them because they will be part of our discussions. Please don't leave a careful reading of the posters to the very end and say "oh yes I wish I had seen that one", because the posters will be part of the discussions you will take part in. They are an essential part of our program.

My next job is a very pleasant one, to introduce our first speaker, Bruce Godwin. Bruce comes from Calgary, is a Civil Engineer, and he has something like 40 years' experience in the field of water resources. Many of you know him from his work with the Prairie Farm Rehabilitation Administration and the Saskatchewan Department of Environment; and then later as Director of the Prairie Provinces Water Board. Bruce knows where the water comes from and where the water goes to, and what it means to people on the prairies. Since he has retired he has set up his own business which has the intriguing name that helps remind him what material he is dealing with. Over to you, Bruce.

REFERENCE

Hector, James, 1961. "On the Capabilities for Settlement of the Central Part of British North America", Edinburgh New Phil. Journal, New Series, XIV, p. 264-267.

SUMMARY AND RECOMMENDATIONS FROM CHS NO. 16-1986
"DROUGHT: THE IMPENDING CRISIS?"

A report given to "Prairie Drought Workshop"-October 11-13, 1988: Saskatoon, Saskatchewan by R.B. Godwin.

The sixteenth Canadian Hydrology Symposium was held from June 4th to June 6th in 1986 at Regina, Saskatchewan. It's subject, "DROUGHT; THE IMPENDING CRISIS", was both appropriate and timely because the Prairie Provinces of Canada were, and still are, in the grip on one of the most severe droughts experienced since our pioneers first came to this arid land.

The papers presented at that symposium, and subsequently published as "Proceedings of the Canadian Hydrology Symposium No. 16 - 1986", contained no summary. That task was assigned to Gordon McKay, John Maybank and myself. The draft paper recently forwarded to workshop participants is the result of our efforts and I will spend the next few minutes discussing this article, concluding with eight recommendations related to it and to the 1986 symposium.

There is nothing new about drought. Recorded history makes frequent reference to past droughts and it is estimated that over 20 droughts were experienced in the Canadian Prairies in the 19th century. There is, however, something threatening about successive droughts. As areas become settled people use more water and they must share the limited supplies that nature originally gave to the region. Consumptive water uses have grown rapidly in the 20th Century and even though we have "drought-proofed" the Prairies we are still unable to survive droughts of several years duration without "tightening our belt" by rationing available water among the more critical uses.

Storage reservoirs, diversions and other structural alternatives have been built, or proposed, to modify and improve our water resources and non-structural solutions such as rationing and water use education programs have been implemented to modify the effects of drought but something else is needed. We must find a way to identify droughts in advance. To do this we need a better knowledge of the hydrological characteristics of drought and be able to quickly determine the probable socio-economic stresses so that we can evaluate the consequences of a variety of mitigative policy and planning alternatives.

The drought of the 1930's is still regarded as the definitive drought in terms of designing structural solutions. In combination with a major economic depression, it intensified the poverty and hardships of prairie residents and forced a quarter of a million people to leave the Prairies. It was a major drought by any definition; a meteorological drought because massive precipitation deficits were observed throughout the entire prairie area, a hydrological drought because surface water and groundwater resources showed major deficiencies and an agricultural drought because for a period in the 1930's virtually nothing grew. Lastly, it was a socio-economic drought, one that devastated both the life styles and the financial capabilities of the Prairie region of Canada.

The papers presented at the 1986 symposium covered many of the factors related to the types of drought we have experienced historically. New computational models, capable of measuring the intensity and duration of droughts as they happened, were presented to the meeting but none of these papers defined a way to predict droughts. Some articles suggested forecasting parameters that might be used in the future including streamflow characteristics, weather radar and satellite imagery. At a subsequent CWRA meeting in Winnipeg, Manitoba weather radar was again suggested and a drought early-warning system for prairie pasture land was proposed. These proposals hold promise for the future and we know that better indices must be developed if droughts are to be identified and controlled. That viewpoint was reiterated by Hugh MacKay at the 1987 CWRA meeting. He said that a basic component of any drought control program was:

> "---a drought monitoring capability which provides decision makers with continuously updated reports on the state of the resource,the chance of drought induced stress and the consequences thereof---".

In some areas of Canada, such as the far north, there is a further concern. The existing data base is limited or non-existent and theoretical parameters derived from other areas may not apply to these ungauged regions. Drought is not a major factor now but, as civilization encroaches on their boundaries, it may become a problem.

Similar shortcomings in both water quality and groundwater data bases are experienced in all areas of Western Canada. More information will be needed from these data bases to ensure that a supply of potable water can be maintained in below normal years and to maximize the usefulness of groundwater as an alternate source. years.

The first, and most obvious way to protect uses against shortages is to develop a dependable supply of water large enough to eliminate all shortfalls. Storage is an obvious solution and, when local supplies are inadequate, diversion becomes a logical choice. These two structural alternatives may not completely protect an area but they form a first line of defense that permits users to survive lower than average years of runoff.

There are also effective non-structural procedures that can mitigate some shortages. They include; water rationing, water pricing and sharing on a basin wide basis to augment supplies in below normal years. Non-structural solutions can not, in themselves, create additional water supplies but they can ease the intensity of droughts and are highly cost effective.

Researchers are working on several innovative ways of increasing the percentage of precipitation that becomes runoff. Forest and prairie snow pack management were two methods discussed at the 1986 symposium. They are part of a larger group of studies that hope to improve spring runoff volumes by modifying the ground surface so that it will retain more winter snowfall to augment spring runoff.

Water management has been the subject of government studies for many years. Their concerns are direct and critical because droughts affect all levels of our society and invariably senior governments are asked to "wave a magic money wand" to repair the damage done by these droughts. These short-term money-intensive programs do help people survive until the drought is over but they do little to correct the original problem. Long-term programs are not as high profile but they minimize the financial aid needed each time an area runs out of water and they do more to stabilize the socio-economic climate related to drought.

If proposed long term programs are to work, a better educated population is required. Governments, at the political level, must understand the true worth of water and have a better understanding of the long-term consequences of issues such as maintenance of an agricultural economy based on irrigation as opposed to preservation of rivers in their natural state. The decisions made must be both socially and financially acceptable to the people that elect our governments so the population at large must also be educated to the value of water resources. We, as water resource professionals, need to explain to these people why this limited resource, water, is critical to our survival. If Canada does not manage water wisely, future generations will be handicapped by ad-hoc decisions made to satisfy vocal minorities.

Some papers were presented to the 1986 conference on the effect that structural control measures have on the natural environment. Environmental aspects must always be considered when a change is planned in a river basin. No project should be built until its potential to modify the environment has been evaluated and figured into the feasibility equation. Furthermore, the predicted environmental effects should be monitored after the project becomes operational to determine if preconstruction estimates were overly conservative or optimistic. In this way planners will be able to make a better assessment of environmental damages on future projects. Until that type of verification becomes available, the evaluation of environmental aspects will continue to be a matter of speculation.

Another area, noted by the 1986 Drought symposium as requiring more research, was the use of groundwater to supplement irrigation water in below normal years. As more investigations are made into the usefulness of irrigation as a long-term drought control measure, with or without groundwater enhancement, it is also to be hoped that economists will find a way to justify the ultimate economic value of irrigation and groundwater when used as protective and preventative devices in a region plagued with drought.

It was clear, from the papers presented at the 1986 meeting, that a basic necessity to research is a more intensive knowledge of all parts of the hydrologic cycle and that research into these components can not be turned on and off like water from a tap if meaningful results are to be obtained.

A major requirement for drought-related research is the development of a total water base. We have a multitude of ad-hoc data bases gathered to serve particular purposes or projects. A lack of continuity and accessibility to these "private" bases creates problems. Our goal should be to combine all of these sub-bases into one country-wide data base for water. Some components, such as precipitation, snow packs, lake levels and river flows, are measured on a continuing basis but other parameters, such as water quality, soil moisture and groundwater, are measured inadequately and with a distressing lack of continuity. An integrated data base of this type could be used to serve holistic research programs capable of predicting the hydrologic cycle sufficiently far in advance to forecast droughts before they happen. Continuing research within the total scope of the problems of drought is needed if we are to produce usable results.

Based on the papers presented at the 1986 Drought Symposium and on the draft report produced by McKay, Godwin and Maybank, I have eight recommendations for your consideration. They are:

1. Future drought research should be based on a holistic approach to understanding all components of the hydrologic cycle with its goal being to provide a drought forecasting tool for the Prairie Provinces of Canada.

2. Research emphasis should be placed initially on the long-term prediction of precipitation because it is the prime mover in any drought forecasting model.

3. The data base for Northern Canada should be strengthened and intensified against a time when future developments make it necessary to evaluate more carefully the water potential of that region.

4. The current data base for water quality purposes is inadequate. More frequent observations, and more extensive coverage, are needed before the potential effect of water quality on water usability during drought periods can be evaluated.

5. Documentation of the actual positive and negative environmental effects of constructed projects, as related to forecasted effects prior to construction, is required on a continuing basis to enable future researchers to improve their

ability to predict the effect of similar future projects.

6. Further research is needed to define the ultimate economic value of using irrigation and groundwater to alleviate long-term droughts.

7. An improved groundwater data base is needed to determine the extent and availability of that resource. The data base should include information on the quality of groundwater in each aquifer to ensure its potability for potential users.

8. More, and better, communication is needed between the technicians and scientists that manage water and the people that control decisions affecting its use to ensure that we use water wisely.

And now my job at this meeting is done. I've summarized the paper we presented, based on the 1986 Drought Symposium, and I've added eight recommendations arising from that paper. I haven't put a dollar figure on any of these eight recommendations but it would be high. Maybe, if we start with the eighth recommendation, the one concerned with better communication, we will eventually be able to implement the other seven.

SESSION 1

DROUGHT DRIVING FORCES

DROUGHT DRIVING FORCES:
A METEOROLOGICAL POINT OF VIEW

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(Paper presented at the Prairie Drought Workshop, Oct. 11-13, National Hydrological Research Center, 11 Innovation Blvd., Saskatoon S7N 3H5, CANADA.)

1. INTRODUCTION

Among the most vivid memories of my early childhood in Kansas are the devastating droughts and dust storms of the 1930's. The most severe of those hot, dry summers, 1934 and 1936, have become the standard of comparison for all U. S. droughts and heat waves. Yet, surprising as it may seem, we have yet to understand why the climate of North America was so anomalous during that particular decade. This lack of understanding of the basic cause(s) of the most severe North American droughts of the century is not unique. The same statement applies to extratropical summertime droughts in general, as well as multi-year tropical dry spells, such as the recent decades-long downturn in rainfall over the African Sahel.

Considering the above remarks, it may seem a bit presumptuous to speak on the topic "drought driving forces". However, in defense of my title, it should be pointed out that we have achieved a rudimentary understanding of the processes behind the El Nino/Southern Oscillation(ENSO) Cycle (Rasmusson, 1985), the single most important source of interannual rainfall variability and drought in the tropics, and one of the drought driving force in some areas of the extratropics. Furthermore, while our understanding of the basic climate system interactions associated with the initiation and maintenance of extratropical drought is admittedly primitive, the data, conceptual framework, and climate system models for examining this question in the context of "internal" climate variability have improved significantly during the past decade.

The chain of drought causality can be examined at various levels. For a meteorologist, it begins with the identification of the persistent atmospheric circulation features associated with a suppression of precipitation. Descriptions of the time-averaged circulation anomalies associated with droughts over various regions of the world have appeared in a variety of papers and reports. A more fundamental understanding is achieved when the forcing mechanisms which initiate and maintain these atmospheric anomalies are identified. The next step is an understanding of these processes in the context of coupled interactions between climate system components, for example ocean and atmosphere. Finally, a knowledge of the factors which determine the time-scales, amplitudes, and frequency of occurrence provides insight into processes behind multiyear-decadal drought regimes.

Like other semi-arid regions of the world, the North American Great Plains has an unreliable precipitation regime. Instrumental and proxy data reveal precipitation variations on a variety of time-scales, from individual anomalous months, to multi-decadal dry regimes. The driving forces behind Great Plains drought may differ from those in other climate zones, as well as vary with time-scale. For example, over large parts of the semi-arid subtropics, e.g. India and the Sahel, rainfall is highly seasonal in occurrence. There is little available soil moisture at the end of the dry season, and non-irrigated crops must depend almost entirely on the precipitation which falls during the subsequent rainy season. In these areas, the driving forces of agricultural drought are those which determine the amount and distribution of rainfall during this single wet season. The situation over the Great Plains is more complex. Over most of North America, a significant amount of the moisture used during the growing season is derived from moisture accumulated during the antecedent cold months (Rasmusson, 1968). Thus, agricultural drought may reflect deficient antecedent conditions as well as deficient precipitation during the growing season. Consequently, processes which affect both cold and warm season climate variability are factors in Great Plains drought. In this regard, it might be noted that cold season extratropical atmospheric variability has been studied far more extensively than warm season variability.

The overall structure of this review is aimed at examining four questions:

1. To what extent is the time/space evolution of drought conditions simply a stochastic process, the integrated effect of essentially random day-to-day weather variations?

2. To what extent can the non-linear internal dynamics of the climate system, interacting with the externally-forced annual cycle, produce the observed patterns of drought?

3. Is there observational evidence for the kind of internal coupled subsystem interactions and feedback processes which give rise to observed modes and scales of low-frequency variability?

4. Excluding the annual cycle, is there persuasive evidence of significant natural external influences on the occurrence and evolution of individual drought events or multiyear-decadal drought regimes?

The outline of this review is as follows. After briefly discussing the concept of drought, I will describe some aspects of "internal" climate variability on time scales of months-decades. The question of anthropogenic influences on drought will not be addressed but the question of whether there is persuasive evidence of significant natural external influences on the occurrence and evolution of drought will then be briefly examined. Some aspects of Great Plains drought, as revealed by instrumental and proxy data will be noted in this context. Comments and speculation on the nature and possible causes of the 1987-1988 evolving pattern of drought follows in the next section. The concluding remarks include a return to the four questions posed in this section and comments on what appear to be some fruitful avenues of research.

2. DEFINING DROUGHT

"When you can measure what you are speaking about and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meager, unsatisfactory kind." (Lord Kelvin).

"Drought is a complex phenomenon involving meteorologic, hydrologic, social, and other dimensions which are difficult to define and quantify universally." (Drought Concepts, Drought Management and Water Supply (Call for Papers). EOS, Vol. 69, No.30 pg. 749 (July 26, 1988).

A fundamental problem in dealing with the concept of drought is vividly illustrated by the juxtaposition of these two quotations. Drought, like "bad weather", is a relative term, and while a universally applicable quantitative definition would serve as a natural starting point in this discussion, no such a definition can be formulated.

One might propose a broad qualitative definition such as "drought is an extended period during which the surface and/or subsurface water supply is significantly less than normal". The four key qualitative terms in this definition are "supply", which implies a demand, "significantly less" and "extended period", which imply an impact, and "normal", which implies an expectation based on a representative "base period". Even such a general definition does not apply to the "mining" of groundwater supplies which is now occurring in many areas.

Drought in one region may represent normal conditions in a more arid region, or during a more arid climatic epoch. Drought is more closely related to percent than to absolute precipitation departures. Consequently, it is a recurrent and often catastrophic feature of semi-arid climates, but is a less frequent and disruptive factor in humid regions. Other well-known conceptual problems are:

a. Analogous to "climate change", the beginning and end of a drought can only be identified in retrospect.

b. Drought is not aridity. Deserts are not regions of perpetual drought; in fact, the concept of drought hardly applies to the most arid regions of the world.

c. Expectation and/or societal requirements must be a factor in the definition of drought. Yet, like climate itself, these factors may change with time, often as a consequence of climate change. How long must an "anomaly" pattern persist before it is treated as the expected regime by those affected? This question is intimately related to the choice of the proper climate "base period", arbitrarily designated as "normal", for evaluating drought.

d. The indexing of drought cannot be separated from the impact to which it is being applied. A variety of impact-oriented indices have been developed to quantify various aspects of drought, but no single parameter, whether it be precipitation, runoff, evapotranspiration, temperature, soil moisture, or crop yields can serve as a universal index. Drought usually results primarily from an extended period of deficient or poorly distributed precipitation, and secondarily from enhanced potential evapotranspiration. Some indices consist simply of a scheme for indexing the integrated effect of precipitation anomalies, e.g. Janowiak et al.(1986). More complex indices attempt a more complete accounting of the surface water balance. In any case, the index should be designed with the impact of interest in mind. For example, the well-known Palmer Drought Severity Index (PDSI) (Palmer, 1965), which has a relatively slow response to precipitation departures, and is often used as an index of "hydrological drought" (Karl and Knight, 1985), while the Crop Moisture Index(CMI) (Palmer, 1968), which has a more rapid response, and is usually a better index of "agricultural drought".

3. INTERNAL VARIABILITY - CONCEPTUAL FRAMEWORK

This section deals with the processes of internal climate variability, where "internal" includes those climate subsystems which can participate in a two-way interaction, e.g. atmosphere, land surface, ocean and cryosphere. Variations associated with extraterrestrial influences, e.g. solar variability, as well as volcanism and anthropogenic effects, are therefore excluded.

3.1 STOCHASTIC CLIMATE MODELS

When viewing drought from a meteorological perspective, questions relating to temporal and spatial scales of atmospheric variability become a major focus. Precipitation is an episodic process whose time and space scales are much smaller than those of the associated synoptic circulation systems. Mesoscale variability is the dominant feature of warm season convective systems, and even the precipitation areas within the relatively widespread and slowly evolving cloud systems of extratropical cyclones often have a strong mesoscale component of time/space variability.

This fundamental time/space scale mismatch between the synoptic scale circulation systems and the much smaller scales of precipitation is reflected in time averaged circulation and precipitation fields. Except for features associated with coastlines and topography, it is often difficult to relate the time-averaged atmospheric anomalies, with dominant spatial scales of 1000 kilometers or more, to the smaller-scale features of the precipitation field, which in some cases may reflect a single event within the averaging period.

A similar fine-structure, e.g. "drought pockets" with scales less than a few hundred kilometers is seen on most drought index maps, either as the dominant scale of variability (Figure 1), or as a subscale superimposed on larger-scale features (Figure 2).

One might then pose the question: can the high-frequency synoptic variability, alone, lead to drought conditions? In addressing this question, the synoptic variability might be analyzed in a stochastic framework. For example, consider the stochastic climate model developed by Hasselmann(1976). In this model, the climate system is viewed as a number of subsystems, e.g. atmosphere, ocean mixed layer, deep ocean, land surface, cryosphere etc., with widely differing response times. The characteristic correlation time of the atmospheric variables is small compared with that of the slower responding subsystems. Their response is modeled as a random walk process, forced by the high frequency atmospheric fluctuations. Since the variance of a random walk process increases linearly with time, its growth is controlled in the model through a low-frequency, negative feedback to the atmosphere, whose time-scale is the relaxation-time scale of the more slowly responding subsystem. Inclusion of this negative feedback results in a statistical balance between random forcing and feedback damping.

If soil moisture was considered as the slow subsystem, its variations would reflect both a high frequency response (episodic precipitation events and variations in evapotranspiration and sensible heat flux) associated with day-to day weather variations), and lower frequency flux variations associated with changes in the total heat and moisture content of the soil.

To my knowledge, the Hasselmann model has not been adapted to the atmosphere/soil moisture system, so it is not possible to say how closely it could reproduce the time/space statistical properties of soil moisture variability. It has, however, been applied by Frankignoul and Hasselmann(1977) to SST variability on monthly-interannual time-scales over the mid-latitude oceans. The results appear somewhat realistic, in terms of the statistical properties of large-scale long-time SST anomalies. As has been pointed out by Namias(1982, 1979, 1978, 1955) and others, large-scale SST anomalies may act as a remote forcing mechanism for drought through their affect on the large-scale atmospheric circulation.

3.2 DETERMINISTIC NON-PERIODIC VARIABILITY

The stochastic view of climate variability represents a significant turnabout from the search for distinct and well behaved climate periodicities that was in vogue during the early decades of this century. With more sophisticated and rigorous statistical analyses, and a less than illustrious track record for predictions based on these rhythms, the game of "cycle hunting" had fallen into some disrepute by mid-century. Except for variations directly related to the annual cycle of insolation, climate time series usually fail to clearly support the presence of regular and distinct intraseasonal-decadal "cycles". While a stochastic approach may provide useful insight into some aspects of climate variability, the concept seems inadequate for describing and diagnosing the physical interactions of many important modes of intraseasonal-interannual variability. For example, there is clearly a positive feedback between ocean and atmosphere in the tropical Pacific associated with the ENSO cycle, contrary to the basic assumption used for the extratropical ocean by Frankignoul and Hasselmann(1977). In addition, atmospheric forcing generates both local and remote ocean responses in the low latitudes, a situation quite different from the simple one-dimensional interactions assumed in Hasselmann's model. More fundamentally, it is clear that these coupled interactions include a significant deterministic component.

No two weather maps are exactly alike. The same statement applies to any realization of low frequency anomalies, whether it be a map of PDSI, the evolution of the ENSO Cycle, or a particular pattern of intraseasonal variability. While a particular feedback or coupled process may be dominant at a particular time or place, there are always a multitude of other forcing processes in operation which influence, to a greater or lesser extent, the evolution from any given set of initial conditions. Thus, while analogs or "models" such as a composite ENSO Cycle (Rasmusson and Carpenter, 1982) may be of some predictive value for a period following the appearance of similar antecedent conditions, their use in projecting the evolution of the anomalies is limited because of the non-linear dynamics of the climate system. The instability of the climate system is such that no matter how closely the initial states resemble one another, the final states will ultimately differ by as much as randomly chosen realizations.

This phenomenon was recognized by Poincare(1881) when he stated that "small differences in the initial conditions produce very great ones in the final one". It was first described rigorously in the now classical paper of Lorenz (1963), entitled "Deterministic non-periodic flow". In a far more general context, the phenomenon has come to be known as "chaos", or "sensitive dependence on initial conditions" (Lorenz, 1986; Shaw, 1987; Gleick, 1987).

Numerical integration of the equations for simple, deterministically evolving non-linear dynamical systems demonstrates that while the system may appear to be evolving randomly, close inspection of the time series reveals certain regularities, even though the series is not periodic. In other words, a non-linear system may exhibit regularity without periodicity. This new way of thinking substitutes for the statement that 'randomness does not imply disorder'" (Shaw, 1987). The nature of the regularities is not always obvious, but can be revealed by suitable analysis schemes (Lorenz, 1986). Numerical simulations of simple systems demonstrate the rich variety of modes which can arise in even the simplest non-linear systems (Shaw, 1987).

For our purposes, the fundamental question becomes: Are the structure and broad band variance maxima observed in climate time series primarily a reflection of internal variability of the climate system? The atmosphere is a turbulent fluid in which initially small disturbances can grow to become the large cyclones and anticyclones associated with day-to-day weather fluctuations. These eddies derive their energy from the internal structure of the atmosphere, i.e., horizontal or vertical gradients of wind, temperature and moisture. Their development is largely controlled by internal atmospheric dynamics, rather than variable factors external to the atmosphere.

Two important new factors therefore come into play when considering lower-frequency climate variations. First of all, interactions between the atmosphere, land and ocean may become important factors. Therefore the processes occurring on these time scales may involve coupled interactions between the atmosphere and land and ocean climate subsystems.

Secondly, for synoptic variability, the slow variation of insolation associated with the annual cycle can be ignored. In contrast, for interannual time-scales, the variance associated with the annual cycle far exceeds that of the anomaly variance which is to be explained. Therefore, the annual cycle likely represents a fundamental control of internal variability on time-scales of a season or longer. Changes associated with the annual cycle of insolation may destroy, modify or enhance an existing anomalous feedback loop in many ways; by its effect on ocean stratification and land surface temperatures, or through changes in the large-scale atmospheric flow, as occurs, for example, over the Indian Ocean in association with the changing monsoon circulations. The pronounced tendency for a phase-locking of ENSO Cycle and tropical biennial anomalies with the annual cycle is persuasive evidence of a strong annual cycle control of the evolution of these oscillations.

4. INTERACTIONS, FEEDBACK AND REMOTE RESPONSE

While intriguing theoretical work has been done in non-linear dynamics e.g. Lorenz(1984A,1984,,1986), we are just beginning to learn about the internal feedbacks and subsystem coupling that result in structured anomaly regimes in the real climate system. On the shorter time-scales, the atmosphere exhibits preferred regional or even global modes of extratropical variability that may persist or evolve over periods ranging up to weeks. Following the paper by Charney and Devore(1979), there was a surge in theoretical interest in these persistent anomaly regimes (Winn-Nielsen, 1986). An understanding of these features may ultimately contribute to our understanding of lower frequency variability as well.

At present, however, it is the structured intraseasonal-interannual time-scale variations of the tropics that are easiest to identify and study. This is true for three reasons; (1) the spectrum of atmospheric variability is far redder in the tropics, i.e. the low frequency signal to high frequency synoptic noise ratio is far higher in the tropics. (2) Related to this is the fact that the three most structured oscillatory fluctuations so far identified, the ENSO Cycle, Quasi-Biennial Oscillation(QBO) and Madden-Julian Oscillation), exhibit their largest amplitude and most systematic behavior in the tropics. Finally, (3) the coupling between surface conditions and the atmosphere is most pronounced in the tropics, thus allowing a more definitive description of the role of coupled interactions.

4.1 TROPICAL OCEAN-ATMOSPHERE COUPLING

As the time-scale of atmospheric variability lengthens to weeks and months, the relative importance of interactions with the longer time-scale climate subsystems would be expected to increase. Perhaps the most significant of these for intraseasonal-interannual time-scales are the ocean mixed layer, the land surface, and cryosphere. The atmosphere is affected through changes in the surface boundary conditions: sea surface temperature (SST), snow and sea ice, soil moisture, albedo (the proportion of incoming solar radiation reflected by the earth's surface) and vegetative cover. These parameters govern, to a large extent, the time-averaged exchange of thermal and mechanical energy between the atmosphere and the more slowly varying land and ocean "memory components" of the climate system. Changes in the boundary conditions can influence the location and intensity of diabatic heat sources which drive the atmospheric circulation. Due to the non-separability of the internal dynamics and boundary forcings in the atmosphere, it is difficult to isolate their effects from the analysis of observed data alone. However, numerical experiments with global general circulation models(GCM's) support the observational evidence that boundary forcings play an important role in both intraseasonal and the interannual variability in the tropics.

Since the oceans constitute 71% of the earth's surface, the role of SST anomalies in short-term climate variability is an important area of climate research (Namias, 1965). The near-equatorial tropics have received particular attention during the past decade, largely in connection with the El Nino-Southern Oscillation (ENSO) phenomenon. At these low latitudes, a close dynamical coupling can exist between ocean and atmosphere on seasonal-interannual time-scales.

The ENSO Cycle has an interannual time-scale and owes its existence to coupled ocean-atmosphere interactions in the equatorial Pacific. The ENSO rhythm is oscillatory, but not periodic. The larger amplitude oscillations, associated with pronounced changes in SST in the equatorial Pacific, recur at irregular intervals of two to seven years, but evolve on a time scale of about two years. This, together with the fact that there are often smaller oscillations spaced at two year intervals, suggests of an underlying but elusive element of biennial variability.

There is a ubiquitous biennial component of variability in climatic parameters. The most pronounced manifestation is the tropical stratospheric QBO, which appears to have an average period of a little over two years. Its amplitude is large--in fact, comparable to the annual cycle--and its course very regular and, therefore, relatively predictable for several months in advance. Biennial variability in the troposphere and at the surface is relatively strong in some parts of the tropics and Southern Hemisphere, but the tropospheric signal is far less regular than the stratospheric QBO, and also varies regionally. There appears to be a pronounced tendency for phase-locking with the annual cycle, which suggests an interaction between internal variability and the annual cycle.

Rainfall time-series from the tropics, notably India, and large parts of sub-Saharan Africa, exhibit a pronounced biennial signal. The relative rarity of back-to-back severe summer droughts over the Great Plains, even during the 1930's (Figure 3), may be related to this mode of variability, although such a statement certainly requires far more convincing documentation.

The higher frequency 30-60 day oscillation was first identified by Madden and Julian(1971, 1972). This oscillation propagates eastward in the equatorial belt, and while it circles the earth in the upper tropospheric wind field, it is primarily evident as large amplitude rainfall and wind fluctuations over the Indian Ocean/western Pacific sector. The oscillation may be an important factor in the timing of the Indian Monsoon's onset and withdrawal, and its active and break periods (Yasunari, 1980). It mimics, in many ways, the more slowly evolving ENSO atmospheric fluctuations, but with its shorter time-scale does not exhibit a similar dynamical coupling with the ocean. Instead the more slowly evolving SST field "positions" the large-amplitude rainfall and low-level wind fluctuations of each individual oscillation. During periods of positive SST anomalies in the central equatorial Pacific, the largest amplitude of these intraseasonal fluctuations occurs farther east than during cold conditions.

The global aspects of this phenomenon have been better defined during the past few years through the work of a number of investigators, for example Lau and Lau(1986), and Knutson and Weickmann (1987), but many basic questions remain as to the source of this variability, and the extratropical response. However, a coupling between atmospheric hydrology and dynamics seems to be a fundamental element of the oscillation.

4.2 ATMOSPHERE-LAND SURFACE INTERACTIONS

The development of drought conditions is associated with local changes in surface albedo, sensible heat flux, evapotranspiration and vegetation (surface roughness). An important question to be resolved is the extent to which widespread drought can influence not only local conditions, but the large-scale atmospheric circulation as well. In particular, is there a feedback between anomalous, drought-related land surface conditions and the drought-sustaining atmospheric circulation? Is this a significant factor in sustaining drought conditions, or is it easily overcome by other influences, e.g. remote response to SST anomalies? Observational studies are inadequate for providing definitive answers to these questions, but a number of GCM experiments have been made, and the results suggest that surface-atmosphere feedback can be an important factor in regional rainfall variability (Mintz, 1984; Shukla and Mintz, 1982). However, because of model deficiencies and insufficient observational data for validation of the simulations, many uncertainties remain. For example, a coupling between land surface anomalies and atmosphere might be quite complex, with both local and remote responses. A resulting area of suppressed precipitation need not coincide with the existing dry region, leading to a migration of the drought area.

4.3 REMOTE FORCING

The causal mechanism which gives rise to persistent circulation anomalies may be far removed from many of the regions of atmospheric response. Such remote responses are a fundamental feature of atmosphere dynamics, and dictate a global view of climate variability. This perspective is certainly necessary when searching for the causes of Great Plains drought. The ENSO Cycle, while primarily associated with massive dislocations of the rainfall regimes of the tropical Pacific-Indian Ocean sector, also results in a less pronounced and reliable pattern of anomalies over parts of North America (Figure 4). Similarly, although the Madden-Julian Oscillation is most pronounced in the tropical belt, it also appears to be associated with wintertime weather regime reversals over parts of the Northern Hemisphere, including North America.

However, it must be clearly be kept in mind, that while the systematic tropical oscillations which have been discussed account for a very significant percent of the intraseasonal-interannual time-scale variance in the tropics, their contribution to a highly systematic pattern of North American variability is quite modest. For example, the PDSI shows essentially a red spectrum over the U.S., with no significant spectral peak in the ENSO or biennial frequency bands (Karl and Koscielny, 1982). Furthermore, a cursory examination of monthly PDSI maps shows little sign of the broadly similar, repeating patterns that characterize the ENSO response of the Pacific-Indian Ocean sector of tropics. This suggests that the relationships which do exist may be more subtle and variable, and that case-to-case differences in the ENSO Cycle, as well as other independent factors, play a dominant role in determining the evolution of the patterns.

5. EXTERNAL INFLUENCES

Anthropogenic effects, arising from processes such as desertification, deforestation, and burning of fossil fuels, are not addressed in this review. Nevertheless, the effect of human activities on climate, both local and large-scale, must be kept in mind when interpreting data, both past and present, and when projecting multi-decadal climate trends. Conversely, the contribution of natural processes to low frequency variations must be duly considered and evaluated when attempting to identify anthropogenic effects.

While there is compelling evidence that radiation changes resulting from orbital variations are a factor on glacial-interglacial time-scales (Hays et al., 1976), diagnostic and model studies during the past quarter-century provide compelling evidence that internal dynamics of the climate system itself is likely the prime source of structured variability on intraseasonal-decadal time-scales. On the other hand, the role of natural external factors in climate variability, particularly solar variability and the effects of volcanic eruptions on the radiational properties of the atmosphere remains unclear. Pronounced decadal-scale fluctuations, such as the U.S. Great Plains droughts of the 1930's and the current long-term Sahelian drought, occur over many semi-arid regions of the world. However, attempts to describe these multi-year modes of variability and relate them to causal mechanisms are seriously hindered by the short time series of precipitation measurements, which usually span no more than a few decades.

An index of Great Plains precipitation during the period of instrumental record is shown in Figure 3. Large decadal-scale swings are apparent, dominated by the negative anomalies of the 1930's, and there may be some suggestion of something like a two-decade period in the variations during this relatively short period.

The value of tree-ring data as an extension of the instrumental record is illustrated in Figure 5, which shows a reconstructed record based on a tree-ring record from Iowa (Duvick and Blasing, 1981). This reconstruction shows that over the last 300 years there were five decades comparable in dryness to the 1930's, four of which occurred prior to the instrumental record. One must look back to the 1820's to find conditions comparable to the 1930's. Regarding these extremely dry conditions around 1820, it is interesting to note that the explorer Stephen H. Long, after crossing the Great Plains in 1820, wrote that the land was "almost wholly unfit for cultivation and, of course, uninhabitable by a people depending on agriculture for subsistence" (Bark, 1977).

Although the Iowa tree-ring record shows a pronounced low frequency component of variability, a visual examination reveals no obvious periodicities in the record. However, Mitchell et al.(1979) found evidence of quasi-periodic variations on a larger spatial scale. Using tree ring data from the entire western U.S., they found indications of rhythmic variations which have been linked with the 22 year Hale sunspot cycle and/or the 18.6 year lunar nodal regression cycle (Mitchell et al., 1979; Bell, 1981; Currie, 1981). After further analysis of the North American tree ring data, Mitchell(1988) has concluded that both components merit further study as bona fide climatic signals, to clarify their physical origins and their potential predictive value. At present, however, they do not constitute a reliable basis for operational climate prediction.

Van Loon and Labitzke (1988) and Labitzke and van Loon(1988) have recently revived the controversial issue of a possible role of the 11-year sunspot cycle through an intriguing line of inquiry. Their analyses seem to indicate a mode of quasi-biennial variability which is modulated by the sunspot cycle. Sophisticated significance tests seem to establish a high level of confidence in the results, but the fact remains that the conclusions are based on only 3 1/2 sunspot cycles. In light of the dismal history of unfulfilled claims of sunspot/weather relationships, it is understandable that many investigators have adopted a "wait and see" attitude regarding these results.

6. GREAT PLAINS DROUGHT:1987-88

The evolution of drought conditions over North America during the two year period October 1986-October 1988 illustrates a number of points which have been discussed. During this period, the PDSI field over the northern and central plains changed from a moist pattern to a broadscale drought regime. The major changes in the pattern took place during the two cold seasons, and during April-June 1988, when pronounced drought conditions spread southeastward from Iowa to Ohio. Thus the evolution of drought conditions was largely associated with precipitation anomalies during winter and spring, rather than during the warmest months of the year.

The upper air circulation anomalies over this sector of the hemisphere during the two cold seasons were broadly consistent with the anomaly patterns observed during many periods of above normal SST over the central and eastern equatorial Pacific, i.e. during a warm phase of the ENSO Cycle such as was occurring during the period. Thus there is a diagnostic analog for these anomalies, which attributes the pattern to coupled ocean-atmospheric interactions in the tropical Pacific. However, an occurrence during two consecutive winters is atypical.

There was no apparent analog for the abnormal precipitation regime of April-June 1988, and it is hard to find a previous pattern that resembles this case, even in a general way.

Nevertheless, there was a pattern of SST anomalies and associated precipitation anomalies in the tropical Pacific of significant amplitude. A recent model experiment by Trenberth et al.(1988) suggests that the persistent anomaly pattern over North America during this period was largely a remote response to the atmospheric heating anomalies which resulted from the tropical precipitation pattern associated with eastern and central tropical Pacific SST anomalies.

Finally, the above analysis of the course of drought over this two year period again raises the nagging question: Is the development and evolution of drought a coherent low-frequency process of the climate system, associated with a well defined evolutionary low frequency signal, such as the ENSO Cycle, or is it simply a relatively uncorrelated sequence of seasonal anomalies, each of which can be diagnosed physically (Karl, 1988). The evolution during this period seems to include elements of both.

7. FINAL REMARKS

Climate variations reflect an integrated response to a multitude of forcings and climate processes. As a first step in understanding the forces which control drought, we search for the dominant processes; those which control the broadscale character of the anomalies, as opposed to secondary controls, which may be easily overridden, or modified.

There is little hope of relating small time/space scale variability to specific climate system interactions. One should avoid "reading the comics with a magnifying glass" and concentrate on drought features whose scale is compatible with large-scale time-averaged anomalies in the atmospheric circulation. Similarly, single station time series provide useful information, but carefully chosen station aggregates provide a better signal to noise ratio and a clearer picture of the broadscale response to a systematic forcing mechanism (Ropelewski and Halpert, 1988, 1987, 1986).

In this context, we return to the four general questions posed in the introduction.

1. To what extent is the time/space evolution of drought conditions simply a stochastic process, the integrated effect of essentially random day-to-day weather variations?

A stochastic approach may provide useful insight into some aspects of drought, particularly the smaller scales of variability which cannot be related to the larger scale time-averaged features of atmosphere variability. However, the conceptual framework is inadequate for describing understanding important modes of "structured" seasonal-interannual time-scale variability. Most fundamentally, it is clear that at least some important climate system interactions on these time scales include a significant or dominant deterministic component which can be analyzed and modeled physically.

2. To what extent can the non-linear internal dynamics of the climate system, interacting with the externally-forced annual cycle, produce the observed patterns of drought?

Diagnostic observational and model studies during the past quarter-century provide compelling evidence that the internal dynamics of the climate system, interacting with the externally-forced annual cycle of radiation, is likely the prime source of structured variability on intraseasonal-decadal time-scales.

3. Is there observational evidence for the kind of internal coupled subsystem interactions and feedback processes which give rise to observed modes and scales of low-frequency variability?

Computer experiments demonstrate the rich variety of complex modes that can be generated from even the simplest kind of non-linear systems. Surprisingly, they also show that the coupling together of systems often increases rather than decreases the degree of order in the composite system (Shaw,1987). Hopefully, this may also apply to coupled interactions between the atmosphere, land, and ocean.

By focusing the discussion in Section 4 on the general nature of well defined oscillations with intraseasonal-interannual time-scales, it was possible to illustrate or at least imply some specific internal feedback processes associated with low-frequency structured variability. In particular, the importance of ocean-atmosphere coupling in global climate variability was illustrated by the ENSO Cycle. In a broader context, correlations have also been found between regional drought and SST anomaly patterns not directly related to the ENSO Cycle, e.g. Atlantic SST and northeast Brazil precipitation (Lough, 1986; Moura and Shukla, 1981; Hastenrath and Heller, 1977) and and Atlantic and global SST and Sahel rainfall (Folland et al., 1986). In addition Namias (1955, 1966, 1969, 1978, 1979, 1982) has discussed evidence of relationships between extratropical SST anomalies and the initiation, persistence, and termination of individual drought episodes over the U S. and Europe.

Hunt and Gordon(1988) have recently reported the results of a climate simulation obtained from a two-level, 21 spectral wavenumber model, which included a seasonally varying solar cycle, land-sea contrast, and smoothed orography. The model includes a primitive hydrological cycle, and predicts cloud cover.

Analysis of the simulated soil moisture variability revealed the development of drought conditions associated with small and subtle anomalies in the time-averaged meteorological parameters, but these "natural droughts" were essentially individual grid-point phenomena, similar to the small scale patterns in Figures 1 and 2, with little spatial coherence. The authors attributed these "grid-point droughts" to non-linearities in the internal climate system of the model. However, it may be of significance to note that in this simulation SST's were fixed at their seasonally varying climatological values. Thus, anomalous ocean-atmosphere coupling was absent from the simulation, raising the question of whether large-scale SST anomaly patterns are a key element in the creation of large-scale drought conditions.

One should not overlook the very sizable decadal scale trends in North Pacific and North Atlantic SST (Namias et al., 1988). At the least they are indexing important low-frequency fluctuations in the climate system which may be related to multi-year or decadal precipitation regimes over North America.

4. Excluding the annual cycle, is there persuasive evidence of significant natural external influences on the occurrence and evolution of individual drought events or multiyear-decadal drought regimes?

While there is compelling evidence that radiation changes resulting from orbital variations are a factor on glacial-interglacial time-scales (Hays et al., 1976), the role of external natural factors in short-term climate variability remains unclear.

Plausible hypotheses or leads regarding the role of external influences should be pursued, but Occam's Razor should be carefully applied in this area. The lack of objectivity and scientific discipline which has plagued this area of investigation in the past should be discouraged through insistence on strict adherence to rigorous statistical procedures, and careful critique of claims of relationships.

Candidates which seem to deserve further study and clarification at this time are the relationship of broadscale western US drought to the 22-year Hale sunspot cycle and the 18.6 year lunar period, and the recent evidence of year-to year climate variations associated with an interaction between the 11-year sunspot cycle and biennial variability in the troposphere.

Lurking as a hidden agenda throughout this review has been the question of the predictability of drought, both short and long term (Rasmusson, 1987). In an early discussion of the prediction problem, Namias(1955) noted "Inasmuch as drought-producing mechanisms are intimately tied to the general hemispheric circulation of the atmosphere it seems clear that correct predictions of this circulation should be the first goal for which to strive......Although extensive studies of the above nature are proceeding in scientific institutions all over the world, and have been since before the turn of the century, no one has as yet uncovered the secret of long-period drought prediction. Now that hemispheric upper-air data are becoming reasonably extensive and a backlog of many years is accumulating, now that solar science and geophysical sciences like oceanography are being greatly expanded, there is greater hope than even that a general solution to the drought problem may be forthcoming".

Namias did not define his time frame for "forthcoming", and while progress has been made, the "general solution of the drought problem" seems as elusive as ever. The appeal in linking climate variations to periodic forcing mechanisms is, of course, the potential for prediction. The emphasis in this review on non-periodic variability arising from the non-linearity of the climate system implies ultimate limits of predictability. The situation for climate prediction is similar to weather prediction. However, a general understanding of the limits of weather predictability was attained during the 1960's and 1970,s, while no comparable understanding yet exists for short term climate prediction.

Also analogous to weather prediction is the ample evidence that the predictability of short term climate variations is a function of initial conditions. For example, the predictablilty of wintertime temperature anomalies over western Canada is undoubtedly enhanced during autumns when the Southern Oscillation Index is extremely high or low. Thus, relating predictability to initial conditions is an important task. The development of a better understanding of the relationship between atmospheric circulation anomalies and anomalous surface conditions seems a promising route to pursue. This will involve coordinated observational studies and modeling experiments, using coupled atmosphere-land-ocean models.

8. Acknowledgments

Thanks are due to C. F. Ropelewski M. S. Halpert for providing the rainfall indices, J. Laver for providing PDSI maps and J. Murray Mitchell for important information on solar-lunar relationships.

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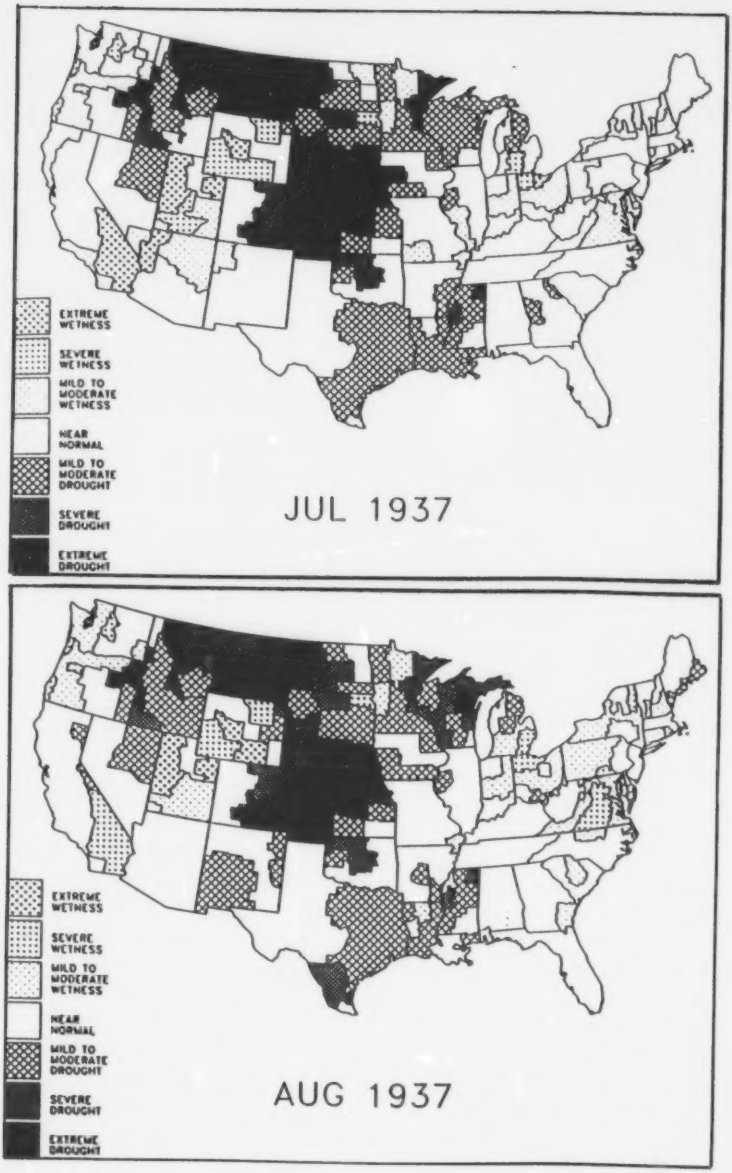

EXTREME WETNESS
SEVERE WETNESS
MILD TO MODERATE WETNESS
NEAR NORMAL
MILD TO MODERATE DROUGHT
SEVERE DROUGHT
EXTREME DROUGHT
JUL 1937
EXTREME WETNESS
SEVERE WETNESS
MILD TO MODERATE WETNESS
NEAR NORMAL
MILD TO MODERATE DROUGHT
SEVERE DROUGHT
EXTREME DROUGHT
AUG 1937

FIGURE 1. Palmer moisture anomaly indices for July and August 1937, illustrating a small-scale variability.

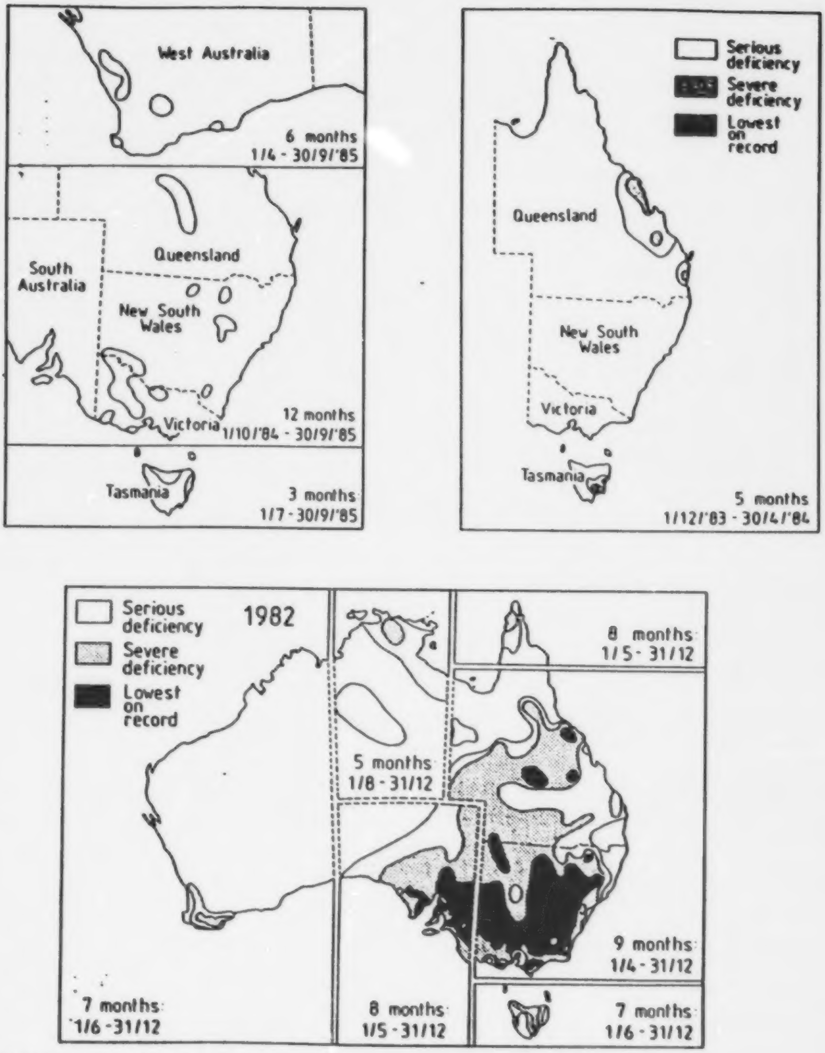

West Australia
6 months
1/4 - 30/9/'85
South Australia
Queensland
New South Wales
Victoria
12 months
1/10/'84 - 30/9/'85
Tasmania
3 months
1/7 - 30/9/'85
Serious deficiency
Severe deficiency
Lowest on record
Queensland
New South Wales
Victoria
Tasmania
5 months
1/12/'83 - 30/4/'84
Serious deficiency
Severe deficiency
Lowest on record
1982
8 months
1/5 - 31/12
5 months
1/8 - 31/12
9 months
1/4 - 31/12
7 months
1/6 - 31/12
8 months
1/5 - 31/12
7 months
1/6 - 31/12

FIGURE 2. Precipitation anomaly patterns over Australia. The lower panel shows the large scale pattern of drought during the 1982-83 ENSO warm episode; the upper panels show patterns during the subsequent period. A small scale pattern appears during both periods, but during 1982 it was superimposed on the large-scale ENSO pattern. (From Hunt and Gordon 1988)

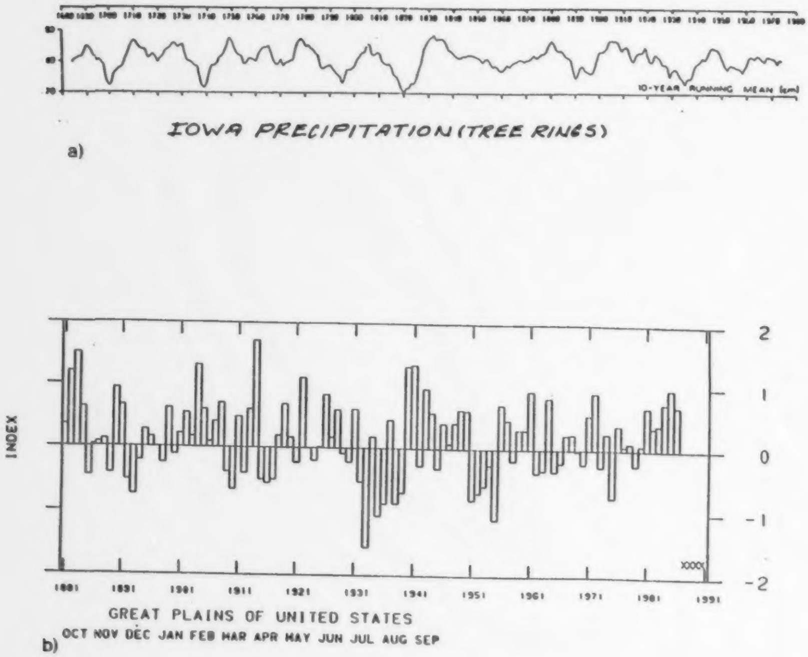
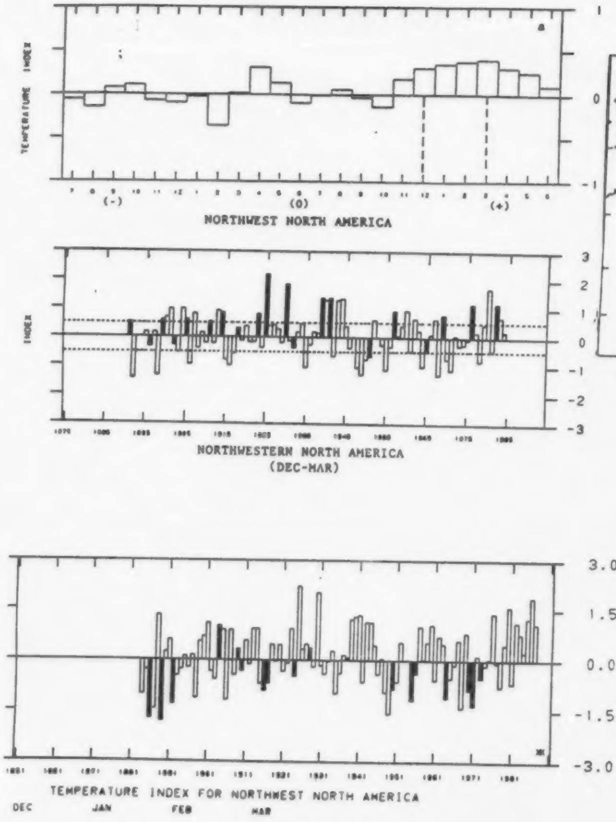


FIGURE 3.
a) Precipitation reconstruction from Iowa tree-ring record.
b) Rainfall index for the U.S. high plains. Year is for October of the water year



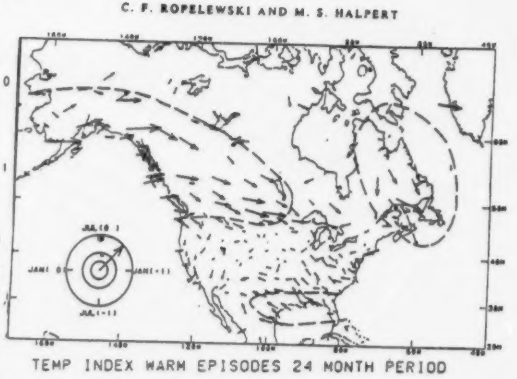

C. F. ROPELEWSKI AND M. S. HALPERT
JUL(0)
JAN(0)
JAN(+1)
JUL(+1)
TEMP INDEX WARM EPISODES 24 MONTH PERIOD

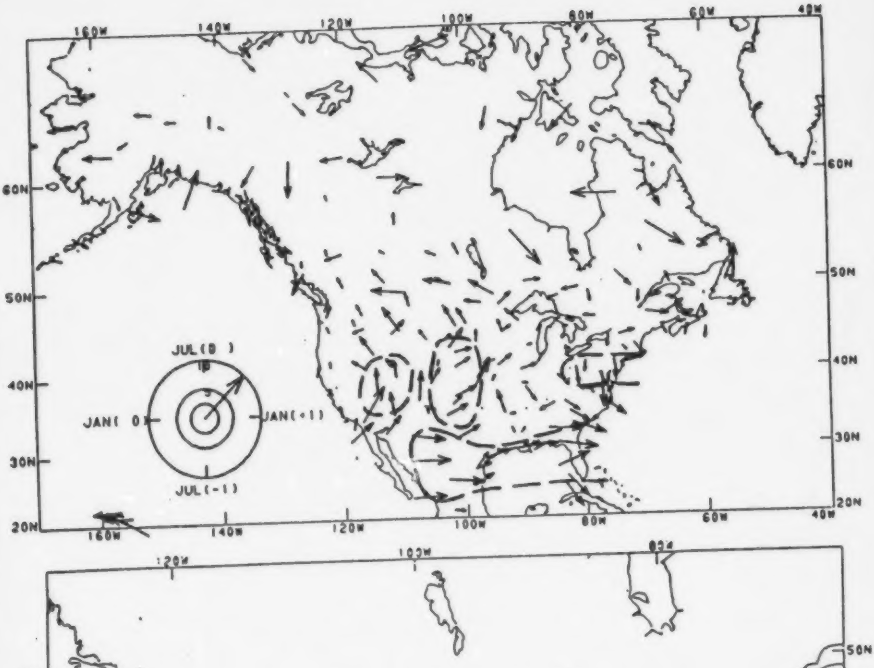
FIGURE 4. **ENSO related fluctuations over North America (From Ropelewski and** Halpert, 1986)

a) Upper Right. Pattern of temperature anomalies during a warm episode. Direction of arrow indicates time of maximum (see Ropelewski and Halpert).

Upper Left. Average temperature anomalies for northwest region during warm episodes.

Middle Left. Year-to-year average temperature anomalies during Dec.-Mar. Dark bars indicate years of warm episodes.

Lower Left. Same as middle left except for cold event years.


160W
140W
120W
100W
80W
60W
40W
60N
50N
40N
30N
20N
JUL(0)
JAN(0)
JAN(+1)
JUL(-1)
120W
100W
80W
50N
40N
30N
20N
PRECIPITATION INDEX
70
60
50
40
30
(-)
(0)
(+)
PACIFIC NORTHWEST REGION

b) Pattern of precipitation anomalies during ENSO warm episodes. Arrows have similar orientation as in 4A. Upper panel is from first order stations. Lower panel is from US climate division data. Average monthly anomaly pattern for northwest US is shown on insert.

THE RELATIONSHIP BETWEEN CANADIAN PRAIRIE DRY AND WET MONTHS, AND CIRCULATION ANOMALIES IN THE MID-TROPOSPHERE

by

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1. Introduction

Canadian prairie dry spells have long been a matter of concern, and this year was no exception. Scholefield et al., 1988, have described the evolution during the past winter, spring, and early summer, of the severe drought over southern Saskatchewan and Alberta.

Although such dry spells have been much investigated in a regional sense, we were unable to find studies relating the Canadian Prairie occurrences to anomalous features of the Northern Hemisphere circulation. This presentation is a brief summary of an attempt to do so. The complete report, to be referred to as K-L, will be published by the Canadian Climate Centre (Knox and Lawford, 1989).

The Canadian Prairies constitute a vast 1800 km reach of territory extending from the Peace River watershed in the northwest, to southern Manitoba in the east. Earlier studies, e.g. Longley (1972) demonstrated how prairie regions had significantly different features in their synoptic climatology particularly with regard to precipitation. This was confirmed by Richman and Lamb (1987) in their principal component analysis of growing season precipitation patterns in southern Canada. Their results applied strictly to 3- and 7-day mean precipitation, but, in a subsequent study, Richman and Lamb (1988) they have indicated similar results for 30-day means.

2. Methodology

We used the Richman and Lamb results as a basis for dividing the prairies into the five zones displayed in Figure 1, and selected 4 representative first-order stations per zone, to determine the respective monthly normalized anomalies of precipitation.

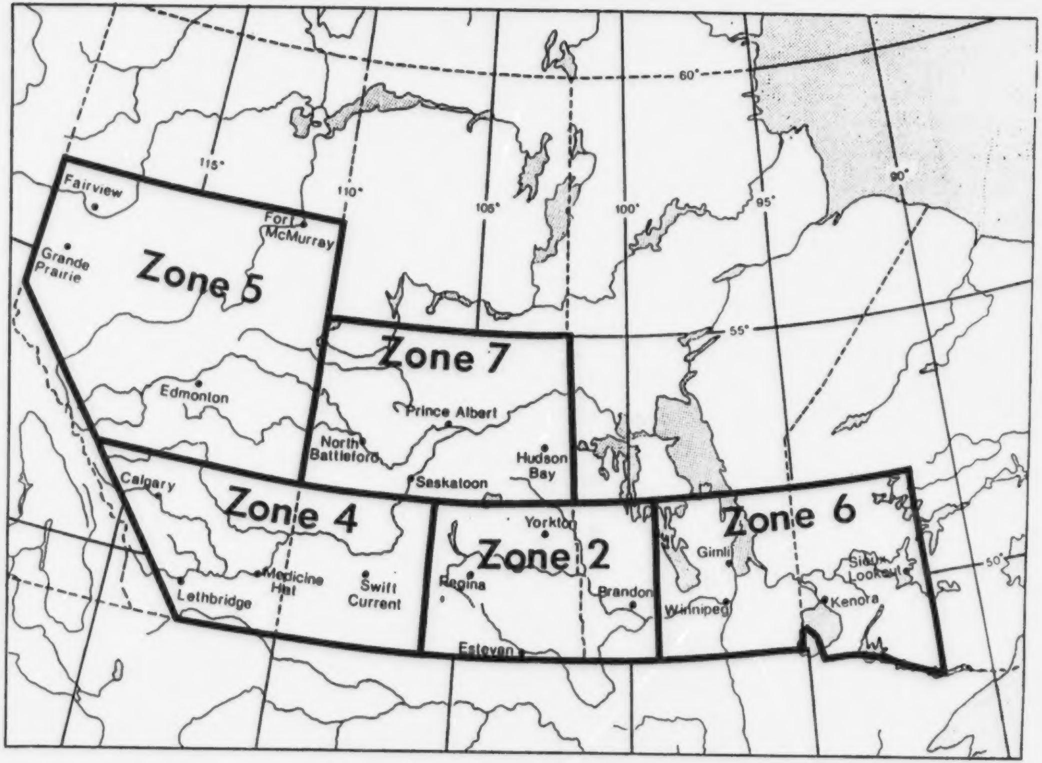

60°
55°
50°
115°
110°
105°
100°
95°
90°
Zone 5
Zone 7
Zone 4
Zone 2
Zone 6
Fairview
Grande Prairie
Fort McMurray
Edmonton
Calgary
Lethbridge
Medicine Hat
Swift Current
North Battleford
Prince Albert
Saskatoon
Hudson Bay
Yorkton
Regina
Estevan
Brandon
Gimli
Winnipeg
Kenora
Sioux Lookout

FIGURE 1. The five climate zones and the stations used to define the monthly precipitation.

Our main focus will be on the months of April, May, June and July when crops are planted and undergo their maximum growth. We define two seasons as follows:

SPRING..........April, May

EARLY SUMMER....June, July

and identify anomalously DRY and WET months within those seasons

All data are for the 40-year period 1946-1985 incl, both at the surface (precipitation) and at the 50 kPa and 100 kPa levels (geopotential height). The heights were extracted from Northern Hemisphere 455 lat.-long. grid-point data sets (15N to the pole) for the respective levels.

Details concerning the normalization of monthly mean precipitation amounts will be found in K-L. The selection criteria were as follows:

(i) For a WET case, the normalized anomaly must be > 0.5

(ii) For a DRY case, " " " " " < -0.5

The results are displayed in Table 1, which shows the dates, by Zone and Regime (DRY /WET) of the ranked qualifying cases for (a) Spring and (b) Early Summer.

The next step was to composite the 50 kPa (and 100 kPa) height analyses for those months common to a specified SEASON/ZONE/Monthly Regime (DRY/WET). Subtracting the normal 50kPa field from the composite yielded the anomaly field, examples of which, for Zone 2 Spring, are shown in Figures 2a (DRY) and 2b (WET). The entire set of these charts, for each of the five zones, both seasons, and the two levels, is available in K-L.

3. Analysis.

In Spring, DRY and WET months are distinguished by distinctly different anomaly fields, not only over the North American continent, but also both flanking oceans. To differentiate more specifically between the salient features of these fields, we used the schematic of N. H. 50 kPa height anomaly teleconnection modes characteristic of the growing seasons shown in Figure 3. The double arrows for the east and west North Pacific (NPO) and North Atlantic (NAO) oscillations terminate at 40N and 60N. In using the schematic to characterize these structures, the following convention was adopted: For both oscillations, negative/positive sign indicates a lower/higher anomaly

TABLE 1. Dates by Zone and Regime (WET/DRY) of the ranked qualifying cases for (a) spring and (b) early summer.

(a) SPRING

ZONE #2		ZONE #4		ZONE #5		ZONE #6		ZONE #7	
WET	DRY	WET	DRY	WET	DRY	WET	DRY	WET	DRY
75 4	49 4	78 4	49 4	48 4	80 4	63 4	80 4	55 4	52 4
70 4	52 4	67 4	77 4	55 4	60 4	74 4	77 4	85 4	80 4
55 4	77 4	53 4	52 4	69 4	70 4	54 4	72 4	73 4	69 4
48 4	83 4	74 4	46 4	62 4	52 4	60 4	49 4	48 4	77 4
79 4	46 4	55 4	62 4	66 4	56 4	67 4	83 4	78 4	74 4
54 4	68 4	54 4	81 4	77 5	56 5	71 4	69 4	75 4	67 4
73 4	82 4	75 4	63 4	84 5	71 5	79 4	52 4	58 4	59 4
65 5	58 5	55 5	82 4	51 5	67 5	57 4	76 5	54 4	56 4
78 5	67 5	81 5	57 5	60 5	58 5	70 4	80 5	77 5	65 4
77 5	80 5	77 5	73 5	64 5	72 5	64 4	52 5	74 5	66 5
74 5	52 5	75 5	58 5	00 0	00 0	65 4	61 5	68 5	71 5
53 5	47 5	82 5	50 5	00 0	00 0	77 5	58 5	84 5	81 5
49 5	71 5	74 5	63 5	00 0	00 0	59 5	00 0	85 5	62 5
62 5	76 5	78 5	00 0	00 0	00 0	62 5	00 0	52 5	56 5
55 5	48 5	00 0	00 0	00 0	00 0	74 5	00 0	00 0	70 5
60 5	00 0	00 0	00 0	00 0	00 0	50 5	00 0	00 0	67 5
00 0	00 0	00 0	00 0	00 0	00 0	53 5	00 0	00 0	57 5
00 0	00 0	00 0	00 0	00 0	00 0	78 5	00 0	00 0	59 5
00 0	00 0	00 0	00 0	00 0	00 0	68 5	00 0	00 0	47 5
00 0	00 0	00 0	00 0	00 0	00 0	70 5	00 0	00 0	00 0
00 0	00 0	00 0	00 0	00 0	00 0	79 5	00 0	00 0	00 0
00 0	00 0	00 0	00 0	00 0	00 0	65 5	00 0	00 0	00 0

(b) EARLY SUMMER

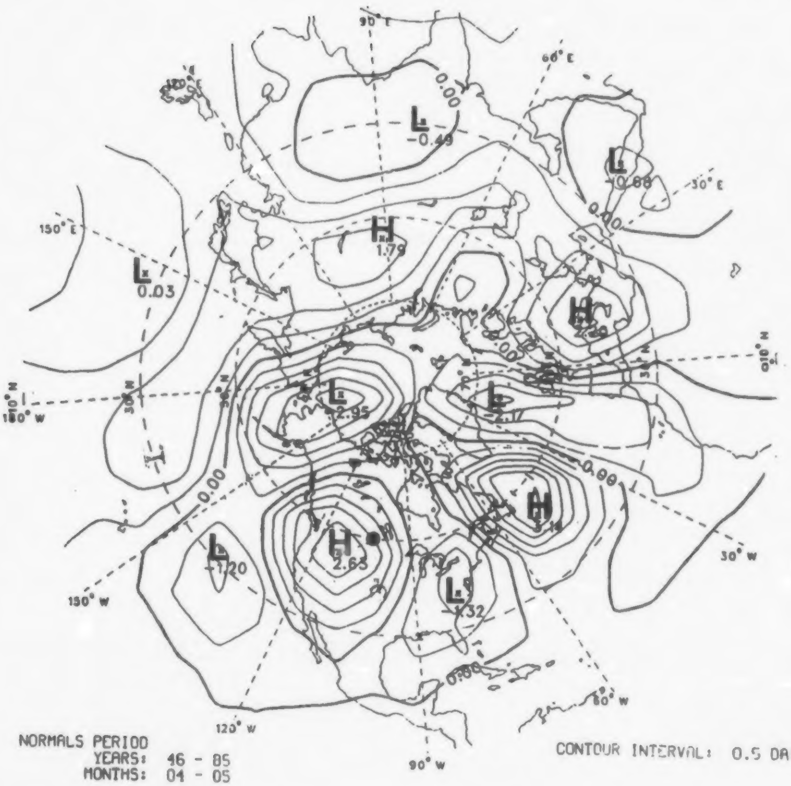
ZONE #2		ZONE #4		ZONE #5		ZONE #6		ZONE #7	
WET	DRY	WET	DRY	WET	DRY	WET	DRY	WET	DRY
53 6	61 6	70 6	85 6	56 6	82 6	84 6	61 6	70 6	64 6
76 6	67 6	63 6	77 6	83 6	63 6	76 6	72 6	65 6	58 6
71 6	74 6	53 6	74 6	71 6	66 6	83 6	62 6	66 6	69 6
47 6	58 6	51 6	61 6	73 6	55 6	81 6	59 6	83 6	77 6
75 6	79 6	65 6	83 6	65 6	67 6	77 6	79 6	76 6	67 6
54 6	82 6	83 7	55 6	61 6	77 6	62 7	76 7	73 6	59 7
63 6	68 6	55 7	49 6	55 7	58 7	58 7	74 7	63 6	84 7
82 7	85 7	50 7	67 7	82 7	85 7	82 7	85 7	71 7	47 7
46 7	51 7	82 7	47 7	83 7	65 7	53 7	60 7	50 7	60 7
70 7	67 7	66 7	73 7	77 7	59 7	48 7	54 7	68 7	75 7
63 7	79 7	00 0	84 7	64 7	84 7	00 0	00 0	82 7	00 0
48 7	60 7	00 0	85 7	57 7	00 0	00 0	00 0	76 7	00 0
83 7	59 7	00 0	00 0	00 0	00 0	00 0	00 0	00 0	00 0
50 7	84 7	00 0	00 0	00 0	00 0	00 0	00 0	00 0	00 0
00 0	47 7	00 0	00 0	00 0	00 0	00 0	00 0	00 0	00 0

SPRING

ZONE 2 DRY

ANOMALY

50 KPA HEIGHT


90° E
60° E
120° E
30° E
150° E
0.00
L -0.49
L -0.88
H 1.79
L 0.03
H 2.29
L -2.95
L -2.17
H 3.14
H 2.63
L -1.20
L -1.32
0.00
30° N
10° N
180° W
150° W
120° W
90° W
60° W
30° W

NORMALS PERIOD
YEARS: 46 - 85
MONTHS: 04 - 05

CONTOUR INTERVAL: 0.5 DAM

Fig.2a

SPRING

ZONE 2 WET

ANOMALY

50 KPA HEIGHT

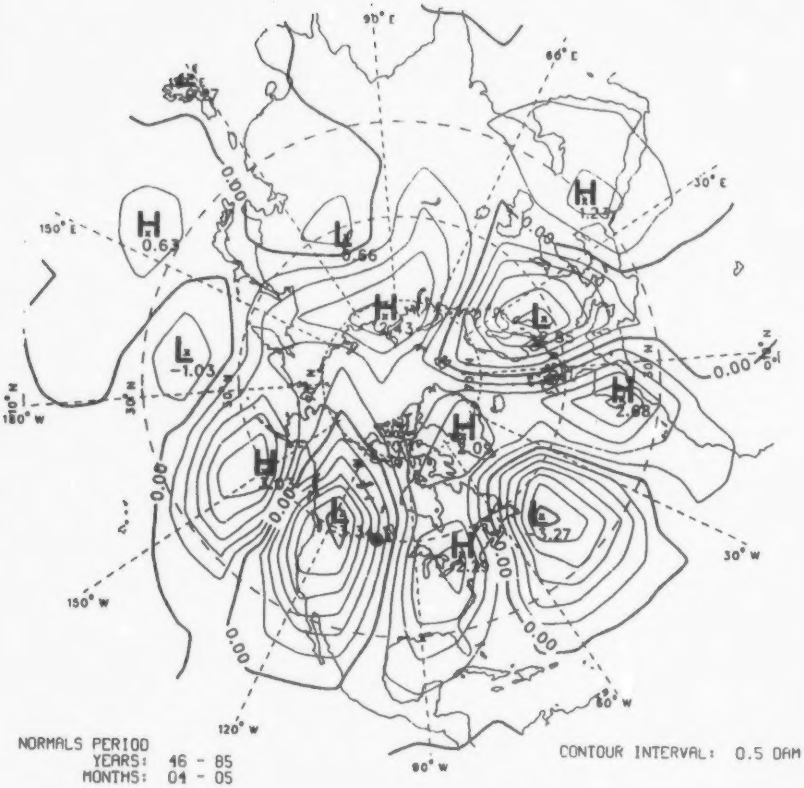

90° E
60° E
30° E
150° E
180° W
150° W
120° W
90° W
60° W
30° W
H 0.63
L 0.66
H 1.23
H 2.43
L 2.85
L -1.03
H 2.88
H 2.05
H 2.03
L 3.34
H 2.29
L 3.27
0.00
NORMALS PERIOD
YEARS: 46 - 85
MONTHS: 04 - 05
CONTOUR INTERVAL: 0.5 DAM

Fig. 2b

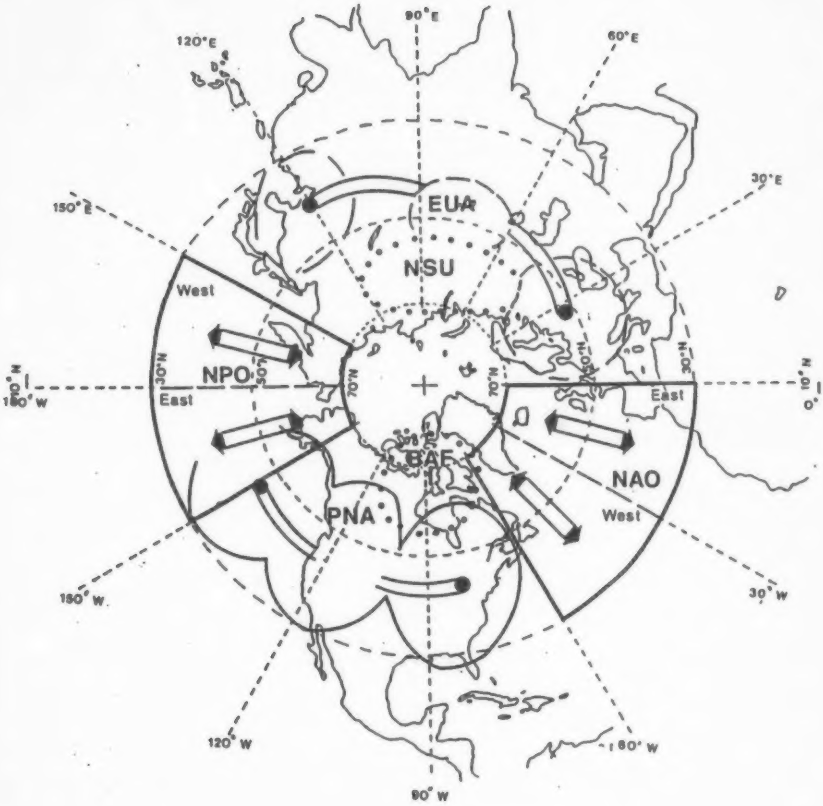

90°E
120°E
60°E
30°E
150°E
EUA
NSU
West
NPO
East
30°N
50°N
70°N
70°N
50°N
30°N
10°N
180° W
0°
10°N
East
NAO
West
BAF
PNA
150° W.
30° W
120° W
60° W
90° W

FIGURE 3 Highly idealized representation of characteristic Northern Hemisphere 50kPa height anomaly teleconnection modes adapted to Spring and early Summer. For definitions and phase sign conventions, see text.

value at 60N than at 40N.

The attributes for the 10 Spring and 10 Early Summer composites are listed in Tables 2 and 3 respectively. The sign of the central lobe of the PNA anomaly is not surprising, although there are zone-dependent differences in the centre location. All Spring DRY months are associated with an amplified positive anomaly centred on average about 10 degrees longitude to the west, and 5 degrees latitude to the south of the geographic centre of the Zone. Moreover the PNO and NAO, both west and east, are consistently negative in Spring, indicating an anomalously stronger west to east flow across both the N. Pacific and N. Atlantic. In practically all cases, diametrically opposite attributes are noted for the Spring WET months. In Early Summer, the results relative to the PNA structure, are similar to Spring over North America, but those relative to the NPO and NAO differ from Zone to Zone.

Tables 2. and 3. also contain information concerning the anomalous wind shear between the 100kPa and 50 kPa levels, for each zone and by season. The K-L Report rationalizes these findings. The "Remarks" column lists other associated synoptic structures (e.g. blocking) and also the dates of prototypes.

4. Concluding comments.

We have completed an analysis of the relationship between WET and DRY months over the Canadian prairies and contemporaneous anomalies in the Northern Hemisphere mid- and lower troposphere circulation during Spring and Early Summer. The anomaly fields arising from the composited charts clearly distinguish the circulations associated with the DRY and WET regimes, and also indicate significant differences from zone to zone. The fields are well defined not only over western North America, but also over the North Pacific and North Atlantic Oceans.

In some respects our investigation is similar to that of Stidd (1954) who used correlation fields (monthly mean precipitation for a state vs 70 kPa height over the USA) to geographically discriminate between precipitation producing flow patterns. The amplitudes of his Winter correlation centres were strong, and his fields for the states contiguous to Canada were consistent with our composite anomalies. However, his patterns for Summer were weak and inconclusive, which could be attributed to his very limited data set combined with the greater local variability of warm season precipitation. We had the advantage of a much longer data set, and because candidates for the composites were based on the more extreme cases, it was possible to obtain coherent anomaly fields for all seasons.

We suggest that our results may well provide a useful

TABLE 2.Composite Anomaly Field Attributes, SPRING.

TELECONNECTION PATTERNS AT 50 KPA FOR SPRING

ZONE	REGIME	ANOMALOUS WIND		NPO		PNA		NAO		REMARKS: significantly amplified anomalies, blocking, prototype dates, etc.
		100kPA	50kPA	WEST	EAST	Centre of nearest anomaly		WEST	EAST	
6	DRY	260	360	- -	- -	+	50N 105W	-	-	Persistent blocking over Wrn Canada occ'n blkg NSU. (Prototypes: Apr., May 1980).
50N 97W	WET	130	200	+	+	-	45N 115W	+	+	Spring-time blocking anomaly pattern over North Atlantic.
2	DRY	280	300	-	- -	+	45N 110W	-	-	Strong mid-latitude westerlies.
50N 102W	WET	090	180	+	-	-	50W 120W	+ +	-	Blocking North Hudson Bay and Baffin Isl.; also over NSU.
4	DRY	270	280	-	-	+	40N 110W	- -	-	Strong mid-latitude westerlies amplified (+)ve Mid Pacific anomaly 47N 180W.
50N 110W	WET	090	160	+	+	-	40N 120W	+	+	Strong blocking NE Atlantic (Prototype: April 1978).
5	DRY	270	280	- -	- -	+	50N 120W	-	-	Above normal westerlies 50-55N (see May 1956 for a prototype).
55N 115W	WET	090	130	+ +	+ +	-	48N 130W	-	+	Very strong Mid-Pacific blocking (+)ve anomaly 55N 180W. (Prototype: Apr., 1948).
7	DRY	250	320	I	I	+	50N 115W	- -	-	Anomalies much attenuated except Baffin Isl.
52N 102W	WET	090	160	+	+	-	50N 120W	+ +	+	Blocking N. Pac., Baff. I., N. Atl (+) Anom 55N 180W. (Prototype Apr, May '55)

TABLE 3. Composite Anomaly Field Attributes, EARLY SUMMER.

TELECONNECTION PATTERNS AT 50 KPA FOR EARLY SUMMER

ZONE	REGIME	ANOMALOUS WIND		NPO		PNA		NAO		REMARKS: significantly amplified anomalies, blocking, prototype dates, etc.
		100kPa	50kPa	WEST	EAST	Centre of nearest anomaly		WEST	EAST	
6	DRY	260	330	-	-	+	45N 105W	-	- -	Strong westerlies 50N. Prototype: June 1961 Amplified positive anomaly 45N 170W.
50N 97W	WET	160	140	+	+	-	45N 105W	+	+	Blocking over Baffin Isl. and W. Atlantic. (Prototype: June 1983).
2	DRY	270	340	-	+	+	45N 120W	-	-	Amplified positive anomaly 45N 170W. (compared with zone 6 DRY; see June 1961).
50N 102W	WET	090	150	-	-	-	47W 130W	+	+	High arctic blocking. (Prototype: July 1982).
4	DRY	I	270	+	-	+	46N 120W	I	I	Amplified positive anomaly 45N 170W. (c.f. zones 6 & 2 dry; see June 1985)
55N 110W	WET	120	140	+	I	-	34N 120W	-	+ +	Amplified negative anomaly 45N 180W. (Prototype July 1983).
5	DRY	270	280	I	I	+	50N 135W	I	+	Amplified (-)ve NSU anomaly 65N 40E. (for prototype see July 1984).
55N 115W	WET	130	150	+	-	-	50N 140W	-	I	For prototype see July 1983.
7	DRY	310	340	I	+	+	51N 122W	-	+	For prototype see July 1984.
52N 102W	WET	090	120	+	I	I	-- --	-	+	Strong blocking NW Europe centred 58N 10E; amplified (-)ve anomaly 45N 180W.

diagnostic tool in connection with evaluating the likelihood of extreme precipitation events (DRY or WET months) over specific zones of the Canadian prairie, given the corresponding 50 kPa and 100 Kpa predicted height fields.

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Session 1 - Working Group Questions and Issues

General

Working Groups should address the question with the same sub-section number as the number of the Working Group. In addition, the Working Groups should address one or two other questions, either of this set (overlapping with other W.G.s is OK), or of their own devising.

1.1 ENSO

What role do equatorial sea surface temperatures (El Nino / Southern Oscillation) play in the initiation and termination of droughts on the Prairies? Is there a latitudinal variation in the potential effects? To what extent is this relationship worth pursuing via research? Who should be doing this kind of research for the Prairies generally and the Canadian Prairie in particular?

1.2 Sunspots

Might there be a relationship between the sunspot cycle and drought? (Note that there seems to be a correlation between the Quasi-Biennial Oscillation, the sunspot cycle and stratospheric winds.) Is this possible relationship worth investigation by climatologists (i.e. beyond investigation by geophysicists) given the apparent lack of a clear physical mechanism relating terrestrial weather to the sunspot cycle?

1.3 Time Scales

How are the physical forcing factors for Prairie drought different on various time scales, i.e. weekly, monthly, seasonal, multi-seasonal (with winter versus summer drought commencement), multi-year drought? What are the sources of the forcing (deep ocean, regional sea surface temperatures, atmospheric circulation blocking, etc.), and how can knowledge be used to direct research to appropriate scientific communities? What linkages in research efforts should be pursued in this regard?

1.4 Drought Types

Considering the three main drought types (i.e. meteorological, agricultural, and hydrological), what can be said of the differences between their driving forces? Is this primarily related to time scales, or something else? How much stochasticity (i.e. lack of fundamental knowledge of the details of the driving force) is involved in the types of drought?

1.5 Antecedent Conditions

To what extent do reduced fall moisture and winter snow pack lead to agricultural drought? Is there a significant dependence on crop type (i.e. are there many sub-types of agricultural drought)?

1.6 Teleconnections

Do teleconnections exist between drought events in various parts of the northern hemisphere, or globally? Can the causes of these teleconnections be described in other than a speculative manner? What research would be needed to elucidate these factors?

1.7 IGBP

The stated goal of the International Geosphere/Biosphere Program: A Study of Global Change (initiated by the International Council of Scientific Unions) is "to describe and understand the interactive physical, chemical and biological processes that regulate the Earth's unique environment for life, the changes that are occurring in this system, and the manner in which they are influenced by human actions". In the planning phase now, the program should be operational about 1990-2010.

How can the prairie drought research community best monitor the activity of this global program to ensure that relevant results and posed questions are known to them in a timely manner? Should drought agencies and researchers attempt to support this program by virtue of their interest in current droughts?

1.8 Cyclical Forcing

What possible drought driving forces may be semi-cyclical in nature (and hence might result in cyclical droughts), and why are they cyclic? What are the approximate lengths of their cycles? Can the cyclic factors most likely to be fruitfully investigated be listed in order? Can they be enumerated in order of the certainty of their existence and influence on drought?

1.9 Volcanic Forcing

What relationship might volcanically induced heavy loading of the stratosphere with aerosols have with drought? Should drought researchers be monitoring the volcanic scientific research?

DROUGHT DRIVING FORCES

Summary

R.G. Lawford - Session Chairman

The session on drought driving forces proved to be a very effective introduction to the subject of prairie drought. Both the keynote speaker, Professor Rasmusson of the University of Maryland, and the invited speaker, Dr. John Knox, a private meteorological consultant, described the meteorological factors which lead to droughts on the prairies. A broad range of issues were subsequently discussed by the seven working groups. This summary reviews the highlights from the presentations, provides a synthesis of the presentations and working group discussions and itemizes the recommendations arising from the working group discussions.

As is evident from his paper printed elsewhere in this report Professor Rasmusson provided a very comprehensive overview of the drought phenomenon. He proposed a framework for analyzing drought processes which identified three classes of fundamental driving forces including stochastic processes, internal dynamics of the atmosphere and external influences. It was recognized that the physics of stochastic processes were rather obscure because of our inability to measure them over the many scales at which they operate. However, to some extent, they are amenable to statistical description. Professor Rasmusson also noted that the processes driving the internal dynamics of the atmosphere are chaotic rather than random. Synoptic scale phenomena and teleconnections are examples of ordered phenomena which emerge within this atmospheric chaos. Over the shorter time scale (1-10 days), internal dynamics are dependent on initial conditions, while on longer time scales (longer than one month), they may be influenced by boundary conditions. The role of external factors in causing droughts is not well known. While scientists are familiar with the consequences of the annual radiation cycle and the long term variations of the earth's orbit, less is known about the possible effects of sunspots, volcanoes and anthropogenically-induced changes to the chemical composition of the atmosphere.

The presentation by Dr. Knox elaborated on the synoptic scale structures which can persist for periods of one month or longer in the atmosphere. He demonstrated that, in the growing season, dry months occur in the southern and central parts of the Canadian prairies when certain height anomaly patterns exist in the 50 kPa (kilopascal) height field. He demonstrated that the placement of the Pacific-North American teleconnection oscillation is important in determining the geographical centre of the dry area. Distinctive height anomaly patterns also exist over the Pacific and North Atlantic Oceans during months which are unusually wet or dry in the Canadian prairies.

The ideas presented in these two papers suggested to the author that while the atmosphere is characterized by chaotic behaviour, structure and order can emerge from this chaos for sufficiently long periods of time to produce dry conditions over a large area. From the working group discussions it was evident that drought also involves the interaction of many different components of the ecosystem. Drought processes occur on a wide range of time and space scales. Causative factors such as evapotranspiration occur at micro and meso-scales. At the other end of the scale planetary circulation patterns appear to determine the areas where droughts are most severe. Time scales are also important. The atmosphere responds very quickly to changes in sea surface temperatures. Moisture fluxes into the atmosphere may involve longer time scales since in some cases they are cumulative and dependent on antecedent moisture conditions.

Drought impacts also range over a number of time and space scales. The effects of agricultural drought are manifested on the small spatial scale of a farmer's field. However these local effects are cumulative and in total can have a devastating effect on a province's economy. Hydrological droughts involve low stream flows and are dependent on the effects of drought throughout an entire watershed. Downstream runoff and ground water table levels reflect the integrated effects of drought over different portions of a watershed.

The seven working groups were asked to consider the questions listed in the preceding section. Four of the groups addressed the questions dealing with sea surface temperatures and teleconnections. It was felt that more research was needed in these areas to determine the influence of sea surface temperatures on drought events. Other questions which the groups considered important involved the effects of antecedent moisture conditions on drought events and the nature of multi-year droughts. There was general agreement amongst the groups that we need a better understanding of meteorological droughts before we can fully address agricultural or hydrological droughts. Some differences of opinion arose regarding the relative importance of antecedent meteorological conditions as a research topic. While some experts thought that the role of antecedent conditions merited further study, others felt that we now know enough about the effects of antecedent moisture conditions and we should be transferring this knowledge to users. Periodicities, sunspots and volcanoes and their relations to drought were also discussed in a number of the groups. In general it was agreed that Canada should continue to be interested in the U.S. work on these topics but that we should not launch independent investigations on these issues. Other related issues which were considered important included:

-the role of the hydrological cycle in general circulation models;
-the integration of hydrological and meteorological data bases;
-the use of proxy data to extend records of drought beyond the instrumental period;
-research on the effects of mitigative drought-proofing practices;
-the influence of dust, radiatively active gases and other industrial activities on the occurrence and intensity of droughts.

An analysis of the working group discussion suggested that drought research should be guided by the following three principles. First, research on drought must be interdisciplinary. The basic drought event is a meteorological drought which can be defined in terms of high temperatures and an absence of precipitation, or some combination of these two basic parameters. However to be useful to society a comprehensive drought analysis must contain information related to the effects of the drought on agriculture, water resources and other social and economic activities. A second principle arises from the realization that droughts are regional events and are not confined to political boundaries. Consequently to fully understand these events we must develop and have ready access to integrated international data bases. It is also recognized that the topic of drought is large and many avenues of research could be pursued. In order to be effective the Canadian scientific community will have to accept as a third principle the need to carefully choose the questions which it studies and to ensure that its research efforts are well focussed.

The working group deliberations resulted in a number of recommendations which could assist in focussing Canada's research efforts. Some recommendations received strong endorsement in that they were developed independently in a number of the working groups. Other recommendations originated in only one or two groups. The extent of the support from the working groups was used to distinguish between high priority and priority recommendations.

The high priority recommendations are as follows:

1. Inter disciplinary research should be conducted into the physical linkages between sea surface temperatures in the Pacific Ocean, the internal dynamics of the atmosphere and the onset, termination and severity of meteorological droughts.

2. Meteorological droughts should be quantified with respect to their spatial and temporal distributions and their intensities. Specific issues to be resolved through these analyses include:
   -Are multi-year droughts discrete events or a succession of seasonal droughts?
   -What role do the stochastic processes of the atmosphere play in the development of a meteorological drought?

3. The linkages between meteorological droughts and other "drought types" need to be understood. Specific questions to be resolved are:
   -What are the relationships between impacts (e.g.crop affected) and the moisture parameters (e.g. soil moisture) which are important?
   -What is the role of antecedent precipitation amounts (fall moisture reserves and snowpack) in alleviating the effects of a meteorological drought on agriculture and water resources?
   -How does the timing of precipitation affect the occurrence and severity of agricultural and hydrological droughts?

4. Research is needed to determine the factors which lead to the occurrence of a meteorological drought and to assess the relative importance of each of these factors. Anthropogenic factors such as greenhouse gases and dust should also be included in these assessments.

Other priority recommendations are listed below:

1. The hydrological component of General Circulation models should be improved and the interactions between the land component and the atmosphere should be more fully understood and more effectively modelled. Until these improvements are made in the models, drought impact studies should be directed at the development of methodologies for impact assessment.

2. Paleoclimatological data and ocean sediment cores should be used to extend the record available for studying sea surface temperatures and prairie drought.

3. When communicating with the media, drought specialists should be careful to clarify which types of drought they are talking about.

4. Research is needed to improve our understanding of man's influence on the hydrological cycle (e.g. Could land use changes make us more vulnerable to hydrological droughts?)

5. A better understanding of the long-term effects of drought mitigation policies on land management practices is needed.

6. Hydrometeorology should become a recognized part of the IGBP at both the national and international levels.

7. A "Centre of Excellence" for drought research should be established at a Palliser Triangle university or college.

SESSION 2

DROUGHT MONITORING, DETECTION AND EARLY WARNING

Drought Advisories Issued by the Climate Analysis Center, NOAA.

by

Jim Laver

Editor's note: In his presentation Mr. Laver discussed the methods used in the Climate Analysis Center to monitor and detect drought. He focussed on the 1988 drought and the following "Drought Advisory 88/12" contains much of the information presented in his address.

DROUGHT ADVISORY 88/12

(JIM LAVER, Ed.)

SUMMARY OF CONDITIONS AND IMPACTS

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NOAA
U.S. DEPARTMENT OF COMMERCE

SEPTEMBER 29, 1988

CLIMATE ANALYSIS CENTER	(CURRENT CLIMATE SERVICES)	(301)763-8071
HYDROLOGIC SERVICES	(HYDROLOGICAL OUTLOOK)	(301)427-7624
NATIONAL CLIMATIC DATA CENTER	(HISTORICAL PERSPECTIVES)	(704)259-0251

ADDITIONAL INFORMATION PROVIDED BY THE METEOROLOGICAL OPERATIONS DIVISION OF
THE NATIONAL METEOROLOGICAL CENTER, THE FOREST SERVICE, USDA, AND
THE REGIONAL CLIMATE CENTERS

DROUGHT ADVISORY 88/12
SUMMARY OF CONDITIONS AND IMPACTS

September 29, 1988

EXECUTIVE SUMMARY

The United States Drought of 1988 was the most severe in the Midwest since 1936. Major crop areas, covering over 25% of the contiguous 48 states, received less than one-half of their normal rainfall during the critical growing period from April through June 1988. The driest and/or hottest periods in over 90 years were recorded in parts of the Plains, Midwest and lower Mississippi Valley. Agricultural impacts were most severe in the Midwest and Great Plains. For example, spring wheat yield was about 50% below the latest five-year average. Below normal river flows and reservoir storage hindered navigation in the lower Mississippi Valley, caused increased restrictions on water usage and reduced the use of irrigation over much of the nation. Forest fires damaged over four millions acres, nationwide, which is more than twice the acreage affected in 1987.

Although the severity of the midwest drought peaked in early July, the origins of drought can be traced back one or more years in different sections of the country. By April 1988, long-term drought conditions already existed over the Tennessee Valley and the southern Appalachians, the northern Plains and much of the West. During the period April-June, these conditions worsened and became extreme. This was caused by record rainfall deficits over the northern Plains and the Mississippi and Ohio River Valleys and record high temperatures across the northern half of the country from the Rockies to the Ohio Valley.

Since the end of June, normal rainfall has returned to some parts of the central United States. This has improved short-term water deficiencies and the agricultural outlook, near the end of the growing season, in the Midwest. Western states, however, continued to receive below normal rainfall from July through the end of August. September precipitation has improved short-term drought conditions and has aided the forest fighting efforts. Long-term drought conditions, however, have improved only slightly. It will take months or years of above normal precipitation in some areas to return riverflow and reservoir conditions back to normal.

This Advisory concludes the series of Drought Advisories issued by the Climate Analysis Center, NOAA beginning on June 21, 1988.

METEOROLOGICAL CONDITIONS

The most intense phase of the United States Drought of 1988 occurred in late spring and early summer and was accompanied by major crop damage and severe navigational problems on the lower Mississippi River. Later in the summer, large-scale forest fires occurred over areas of the Northwest and Rocky Mountains. Many chronic drought problems still exist, although the critical stage has now passed. This Advisory is intended to sum up the drought situation and present some of the historical significance of conditions during the period from April through August.

ACUTE DROUGHT PERIOD: The period April-June was abnormally dry over a large part of the United States. As shown by Figure 1, a large area of the Mississippi/Missouri watershed had less than 50% of normal precipitation. These precipitation deficiencies were as great as six inches in the Mississippi Valley area (Figure 2). Deficits generally existed throughout the country, except for small areas of excess precipitation in the normally dry Southwest and the far West.

The significant change to more normal rainfall occurred during July-August, as shown in Figures 3 and 4. However, an additional deficit of about four inches (Figure 4) amplified the drought problems in some midwestern areas, especially parts of Illinois.

A view of the temporal variation of the areas covered by the severe dryness is shown in Figure 5. As can be seen, up to 26% of the contiguous United States was abnormally dry at the end of June, but this was followed by a steady decrease in the area of dryness after that time.

Rankings of the precipitation deficiencies for the April-June 1988 period are shown in Figure 6. They were calculated by using 58 years (1931-1988) of surface observations. Many climate divisions experienced the driest three-month period on record. An equally large area was in the 2nd-5th driest category.

ASSOCIATED CIRCULATION FEATURES: The causes of this extreme dry period over such a large portion of the United States cannot be directly determined. However, it is clear that this drought was associated with an unusual displacement of the jet stream. The prevailing jet stream track during June 1988 is shown in Figure 7. The June 1988 position is also fairly representative of the two previous months and indicates an upper-air ridging pattern over the north-central States and south-central Canada. Such ridges deflect rain bearing storms away from the center of the United States. The normal flow, usually associated with adequate precipitation throughout the United States, is also depicted. By July (Figure 7), a change to near normal is evident with the reduction of amplitude of the persistent ridge. This re-established a more normal storm-track pattern.

SUMMER HEAT: While the spring and early summer of 1988 were among the driest on record, the summer season can be characterized as one of the hottest on record, predominately within the northern half of the United States. This is shown by the seasonal departure of average temperature from normal (Figure 8). Several short-term heat waves resulted in the hottest summer in the northern Plains in at least the last 38 years (Figure 9). Only a small area over Texas and New Mexico recorded temperatures more than 2°F below normal.

Many heat records were broken during the summer of 1988. As can be seen from Figure 10, the normal number of days with maximum temperatures of 90°F or higher in the northern part of the United States is less than 40 days. Parts of the northern Plains, the Great Lakes and the Northeast normally have less than 10 days. However, Figure 11 shows that practically all of the United States experienced at least 20 days with maximum temperatures of 90°F or higher. Most of the central Plains and the Midwest experienced 40-60 days with temperatures reaching 90°F or above, which is at least 20 days more than normally expected.

PERFORMANCE OF THE OUTLOOKS: Precipitation outlooks issued for the period April through mid-July correctly indicated dryness in the Midwest in almost every case, but these forecasts generally understated the areal coverage and indicated conservative probabilities. Figures 12 and 13 show the most relevant 90-Day Precipitation Outlook and its verifying pattern, respectively. Except for April, the monthly rainfall outlooks scored well because of the emphasis on midwestern dryness.

The 90-Day Temperature Outlook for the summer (June-August) correctly pointed toward warmer than normal weather in many of the areas that experienced intense heat. Figures 14 and 15 show the summer Temperature Outlook and the verification. This forecast attained a much better than average score, as did the monthly outlooks from June to August taken as a group.

LONG-TERM DROUGHT: Although the focus has been on the period beginning in April as the most acute phase of 1988 Drought, the roots of some of this anomaly were already in place much earlier. This is reflected by the Palmer Drought Severity Index (PDSI) chart for April 30, 1988 (Figure 16). The PDSI represents the longer term groundwater balance and, even in April, indicated some extreme drought conditions in the Tennessee Valley and the northern Plains. Dry conditions in the Southeast already had a three or four year history. Conditions in the northern Plains steadily worsened due to the previous dry autumn and winter, followed by a lack of snow runoff in spring of 1988. The mountains of the far West experienced a shortage of winter snow. Some areas of the Pacific Northwest had similar deficits over the past two winters.

Especially evident from the PDSI of July 9, 1988 (Figure 17) is the large expanse of the extreme drought rating, especially in the northern Plains. Most of this extreme rating resulted from the lack of sufficient precipitation during a normally dry period. One inch (or less) per month fell in many locations which usually receive about two inches per month.

Changes in the PDSI were rapid between the end of April and the middle of July, as shown by Figure 18. The percent of area covered by ratings of severe or extreme drought rose rather dramatically to a high of about 40% of the total area of the contiguous United States.

HISTORICAL PERSPECTIVE

PRECIPITATION: When precipitation is averaged across the entire country, the April-June 1988 period was the driest for that period since at least 1895, the earliest year for which a national average can be reliably calculated. The April-June periods of 1934 and 1936 were second and third driest (see Figure 19). Although rainfall increased during the last half of summer, the June-August period in 1988 was still considerably below normal. Rainfall deficiency in 1988 was severe enough to rank the nationally averaged precipitation during the January-August period as the second driest on record, just behind 1934.

While much of the country was experiencing drought, about one percent of the Climate Divisions (sections of Louisiana and New Mexico) recorded the wettest summer and wettest January-August periods on record in 1988.

TEMPERATURE: When temperatures are averaged across the entire United States, (using preliminary Climate Division data) the summer of 1988 (June-August) ties with 1934 for second hottest (see Figure 20). The hottest summer was 1936. Nationally-averaged temperatures for the first eight months of 1988 (January-August) were also significantly above normal.

DROUGHT RECOVERY: The near-term prospects for recovery from the long-term drought vary from state to state. In order to estimate precipitation needed to relieve long-term drought conditions by November 30, 1988, the PDSI at the end of August was used (Figure 21). A PDSI drought is considered to have ended when the index approaches zero. The seasonal total precipitation for September through November (1895 to 1987) was examined in order to provide a historical measure of the chances of receiving adequate precipitation to end the PDSI drought by November 30. The amount required, in this case, varies from under 10 inches in parts of the West and northern Plains to 21-25 inches in the normally wetter Southeast. The probabilities associated with these required amounts range from 1 in 50 in the West and Southeast to 1 in 1000 in the northern Plains (see Figure 22). Thus, while we have seen some improvement in recent weeks for some areas affected by drought, the chances are not favorable for ending the long-term drought by November 30 in the areas of the United States most severely affected.

REGIONAL CONDITIONS: Precipitation rankings from the Midwest Regional Climate Center (Figure 23) show how significantly the midwest agricultural area was affected by drought. Many areas experienced one of their five driest growing seasons (April-August) in 93 years. A report by the High Plains Regional Climate Center indicates that lack of rainfall in the late growing season of 1987 resulted in low soil moisture at the beginning of the 1987-88 winter. Below normal winter rainfall in many parts of the Plains and the Midwest prior to planting time in 1988 resulted in no soil moisture recharge. These conditions added to the impact of the dryness during April-August which followed in many areas.

Climate Division information back to 1895 indicates the regions which recorded their driest April-June period in 93 years (Figure 24). (Note that this is a longer reference period than was used in Figure 6). The dry areas covered parts of the Mississippi River drainage basin and Great Lakes region.

Record-setting heat occurred this year in 45 Climate Divisions during the summer. The areas having the hottest summer in 1988 were generally in the central Rockies to northern Plains region, the Great Lakes area, and the Northeast (see Figure 24). Two Climate Divisions (in New Mexico and Wyoming) had the hottest January-August period in 1988.

A comparison with past years is shown in Figure 25. The April-June period was among the driest in modern times over large sections of the country. In comparison, 1987 is viewed as a relatively dry year over much of the southeastern portions of the country and the analysis shows only small areas with precipitation deficiencies comparable to the current year. The areal extent of extreme precipitation deficiencies for April-June 1988 even surpassed that of the dust bowl years of 1934 and 1936.

For the nation as a whole, the summer of 1988 was among the hottest on record. It ranked 3rd warmest since 1930 (using a slightly different method than in Figure 20) and far surpassed last year's Southeast United States heat wave. The pattern of extreme temperatures was comparable to the summers of 1936 and 1934 (Figure 26).

DROUGHT IMPACTS

SUMMARY: Significant drought impacts during 1988 are depicted in Figure 27. While the primary causes may be the meteorological conditions during 1988, in many areas unfavorable conditions began in earlier years. The situation in 1988 amplified these conditions.

AGRICULTURE: The yields per acre of spring wheat, corn and soybeans were especially influenced by the drought (Figure 27). Final yields are not yet available, but United States Department of Agriculture estimates as of September 1, 1988 indicate that spring wheat yield will likely be the most strongly reduced. Spring wheat yield is expected to be about 49% of the average over the past five years (1983-1987). Similarly, the corn yield is expected to be about 64% and the soybean yield about 76%.

RIVERFLOW AND RESERVOIR CONDITIONS: Below normal runoff during the past two years in the West has resulted in below normal streamflow and reservoir levels. Many of the reservoirs did not fill this season and a significant impact was reported in the agricultural communities. Record low flows were also reported in the Columbia River Basin (Figure 27). Many hydrologic regions showed sizable rainfall deficits, for example, during the period April-June 1988 (Figure 28). Five zones had record low (area averaged) amounts.

Low flows and below normal reservoir storage severely impacted agricultural communities, especially in non-irrigated areas in the Midwest and West. Navigation has been severely hindered, particularly along the lower Mississippi River below St. Louis, the lower Ohio River near the confluence with the Mississippi River and along the lower end of the Apalachicola River in northwest Florida. Water restrictions, voluntary or involuntary, have been reported in areas impacted by water supply shortages.

Below normal precipitation and runoff in the central United States during the past year have resulted in some of the lowest river levels seen in the past 50 years on the Mississippi River system. For example, all-time record lows have occurred at Memphis, Tennessee and Helena, Arkansas along the lower Mississippi River. Numerous streams and smaller rivers completely dried up during the summer months. Water routed through the Missouri River system from reservoir releases in South Dakota played a major roll in preventing the lower Mississippi River from experiencing even lower levels than occurred this summer. The Ohio River system, which is normally a major contributor to the Mississippi River system, was supplying 20% of its normal input to the Mississippi during one period. The upper Mississippi River also experienced very low flows.

In the Southeast, as a result of below normal precipitation during the past two years, record low river levels were reported throughout much of the region, with less than desirable inflow to reservoirs. Throughout Florida, however, recent rains have resulted in near normal to above normal streamflows.

River and lake levels continue to decline over much of the Great Lakes region. During July, Lake Michigan and Lake Huron levels dropped below the long term average for the first time since October 1977 while Lake Superior continued below the long term average.

As for the Southwest and the Northeast, normal to above normal snowpack and above normal runoff this past winter, and intermittent heavy rain events this spring and summer, have resulted in near average streamflow throughout much of the region. Average to above average inflow into reservoirs has occurred in the lower Colorado and Rio Grande Basins.

During the first part of September, river levels either remained unchanged or continued to decline over much of the country. The exceptions were central and north Florida, where major flooding occurred, and in the Gulf Coast region from Louisiana to northwest Florida, where heavy rains from Hurricane "FLORENCE" caused moderate flooding.

FOREST FIRES: The satellite image of smoke plumes created by the forest fires within and around Yellowstone National Park was acquired on 7 September 1988 by the AVHRR Data Acquisition and Processing System at the United States Geological Survey's EROS Data Center in Sioux Falls, SD (Figure 29). The image includes a portion of the scene from the NOAA-9 satellite at approximately 16:32 P.M., Mountain Daylight Time. Smoke from the forest fires in Wyoming extended into eastern regions of North Dakota, South Dakota and Nebraska.

The acreage burned and the number of forest fires (as of September 19) are depicted in Figures 30 and 31 with similar data for 1987 also shown. More than twice the acreage has burned during 1988 as compared with the same period in 1987.

The National Interagency Forest Fire Center (NIFFC) has provided the following interim data on forest fire activity. More detailed summaries are available from NIFFC and a final summary will be published by NIFFC at the end of the forest fire season (by late December 1988).

FOREST FIRE SUMMARY FOR WESTERN STATES - 1988 SEASON THROUGH SEPTEMBER 27

STATE	LARGEST FIRE	ACRES	FIRES>10K ACRES	>300	TOTAL ACRES
ALASKA	A043	566,800	26	52	2,213,000
ARIZONA	PEAK	12,025	1	16	35,900
CALIFORNIA	49ER	35,300	5	42	184,700
COLORADO	I DO	16,000	1	19	45,100
IDAHO	SILVER CREEK	69,400	8	26	337,700
MONTANA	CANYON CREEK	247,200	14	44	824,300
NEVADA	USAF 4	12,100	1	28	67,100
OREGON	TEPEE BUTTE	59,900	2	33	110,400
S.DAKOTA	GALENA	16,300	1	2	20,200
TEXAS	ALBANY	265,000	1	2	267,000
UTAH	WHITE ROCKS	15,800	1	22	42,900
WASHINGTON	DINKLEMAN	53,500	3	14	112,600
WYOMING	CLOVER/MIST	411,500	11	27	1,645,300

OUTLOOKS

FOREST FIRE OUTLOOK: According to the daily situation report (September 26) from the Forest Service/USDA, recent wet, cool weather over much of the northern Rockies was assisting crews in containment and mop up of remaining fires. There have been few new starts and resource availability is improving. With favorable weather dominating the northern Rockies, the Forest Service expects continued improvement in the fire situation as many fires are brought under containment.

WEATHER OUTLOOK (90-Day): The 90-day Outlook for October through December (Figure 32) places cool weather in the Plains and moves the warm conditions away from many of the summer's heat wave areas to the Southeast. It brings wet weather to most of the Mississippi Valley, but leaves uncertain the prospects for early precipitation in either the mountains of the West or the drought-stricken northern Plains.

HYDROLOGIC OUTLOOK During the fall months, average to above average streamflow is expected throughout the Atlantic regions as well as in the Texas Gulf, the Rio Grande, and the Arkansas-White-Red River Basins. Elsewhere, streamflow is expected to continue to be below to much below average (Figure 33). However, isolated heavy rainfall events may produce short term localized flooding on smaller rivers and streams. Considering historical precipitation-producing weather systems and runoff patterns over various parts of the country, the following is the best estimate of what would be needed to bring the water supply back to normal:

Ohio/Lower Mississippi Basins: A series of systems producing at least 8-12 inches of rain over much of the Ohio River Basin over a 2-4 week period. Historically, the probability of experiencing this weather scenario is very low during summer with the chances increasing during fall and extending through early spring.

Missouri Basin: Two to three years of above normal winter precipitation over the mountainous headwaters of the basin followed by above normal snowpack runoff for each of the years.

California: One year of normal winter precipitation followed by normal spring snowpack runoff.

Upper Mississippi/Great Lakes Basin: Two to three years of above normal winter and spring precipitation followed by above normal runoff for each of the years.

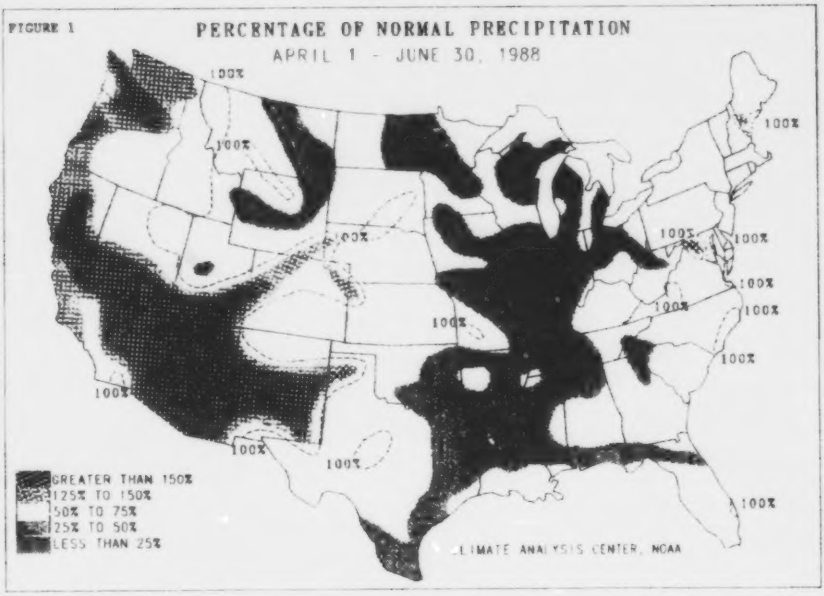
The Reservoir Storage Outlook for Fall 1988 is depicted in Figure 33.

This Advisory is a technical summary of the spring and summer United States drought conditions. The analyses are preliminary and have been produced from recent weather and climate data. The Climate Analysis Center (CAC) will continue to monitor drought conditions in the United States using input from other NOAA offices, Regional Climate Centers and State Climatologists in addition to normal data analyses of the National Weather Service. The CAC does not expect to issue any further Drought Advisories during 1988.

Questions should be directed as follows:

Area of Concern	Source	Number
Technical/Current Climate	NWS, Climate Analysis Center	301-763-8071
Public Information	NWS, Public Affairs	301-427-7622
Hydrology	NWS, Hydrologic Services	301-427-7624
Fire and Aviation Management	USDA, Forest Service	703-235-3838
Historical Perspective	NESDIS, National Climatic Data Center	704-259-0251
Regional Perspectives	High Plains Regional Climate Center (RCC)	402-472-6706
	Midwest RCC	217-244-1488
	Northeast RCC	607-255-1749
	Southeast RCC	803-737-0811
	Southern RCC	504-388-6184
	Western RCC	702-972-1676

FIGURE 1

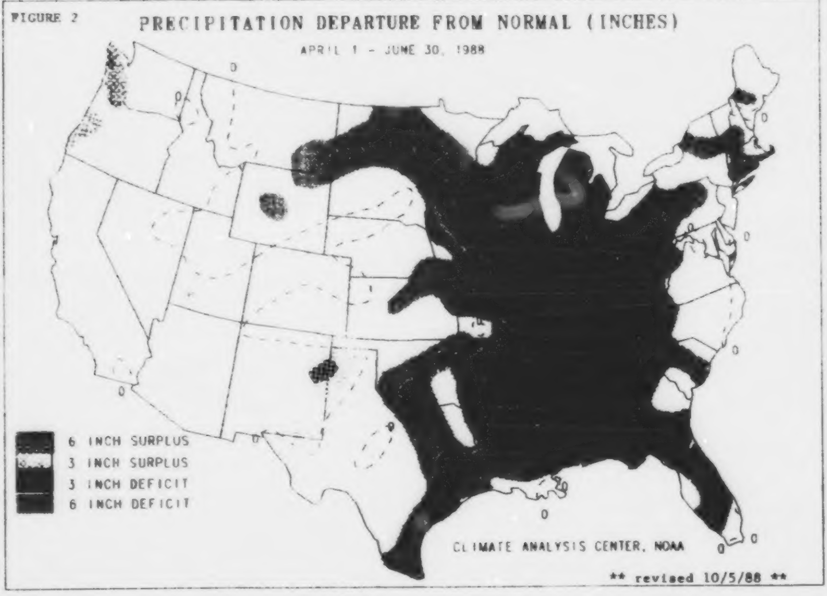


PERCENTAGE OF NORMAL PRECIPITATION
APRIL 1 - JUNE 30, 1988

100%
100%
100%
100%
100%
100%
100%
100%
100%
100%
100%
100%
100%
100%
100%
GREATER THAN 150%
125% TO 150%
50% TO 75%
25% TO 50%
LESS THAN 25%

CLIMATE ANALYSIS CENTER, NOAA

FIGURE 2



PRECIPITATION DEPARTURE FROM NORMAL (INCHES)
APRIL 1 - JUNE 30, 1988

0
0
0
0
0
0
0
0
0
0
0
6 INCH SURPLUS
3 INCH SURPLUS
3 INCH DEFICIT
6 INCH DEFICIT

CLIMATE ANALYSIS CENTER, NOAA

** revised 10/5/88 **

FIGURE 3

PERCENTAGE OF NORMAL PRECIPITATION
JULY 1 - AUGUST 31, 1988

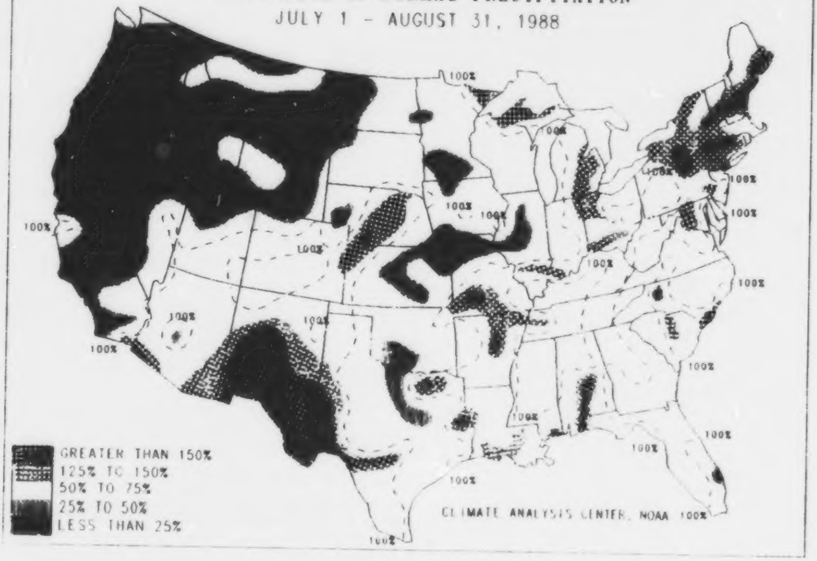

GREATER THAN 150%
125% TO 150%
50% TO 75%
25% TO 50%
LESS THAN 25%
100%
CLIMATE ANALYSIS CENTER, NOAA

FIGURE 4

PRECIPITATION DEPARTURE FROM NORMAL (INCHES)
JUL 1 - AUG 31, 1988

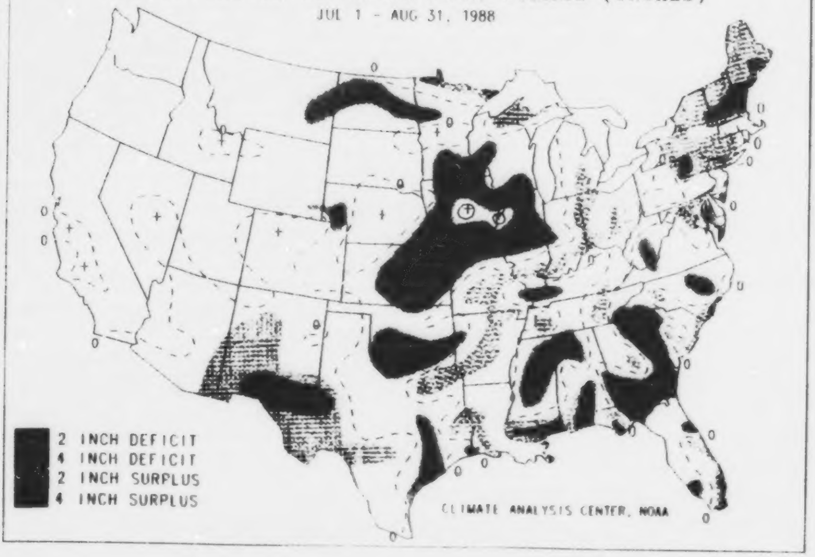
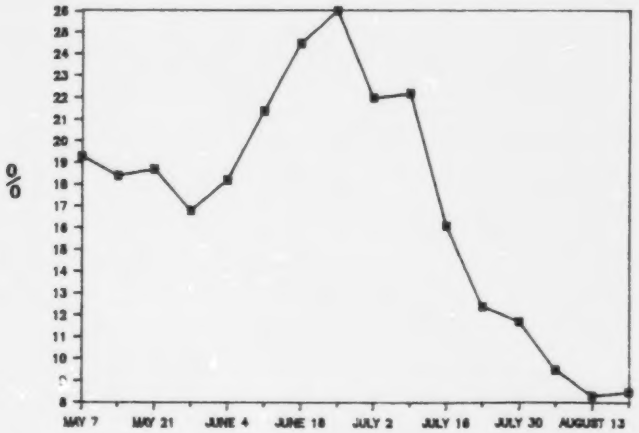

2 INCH DEFICIT
4 INCH DEFICIT
2 INCH SURPLUS
4 INCH SURPLUS
0
+
CLIMATE ANALYSIS CENTER, NOAA

FIGURE 5

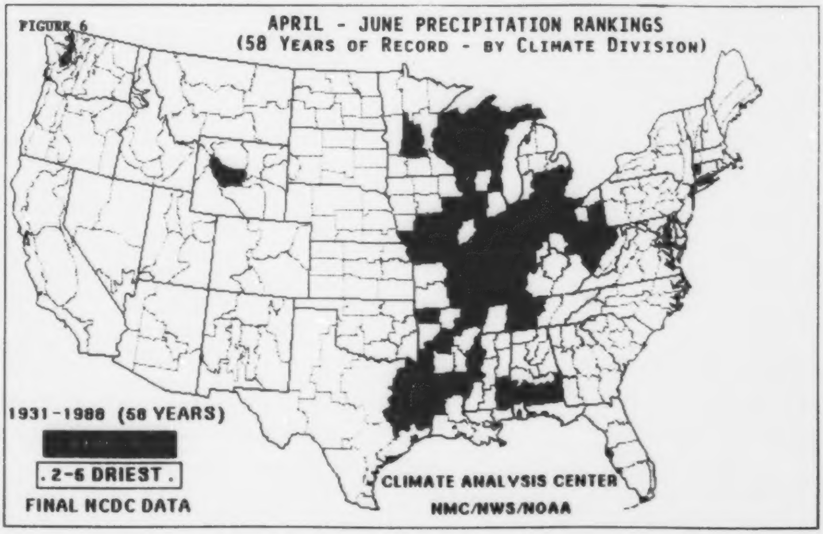
PERCENT OF AREA OF UNITED STATES WITH <50% OF NORMAL RAINFALL
(EACH CASE IS FROM APRIL 1 TO DATE INDICATED)



CLIMATE ANALYSIS CENTER, NOAA

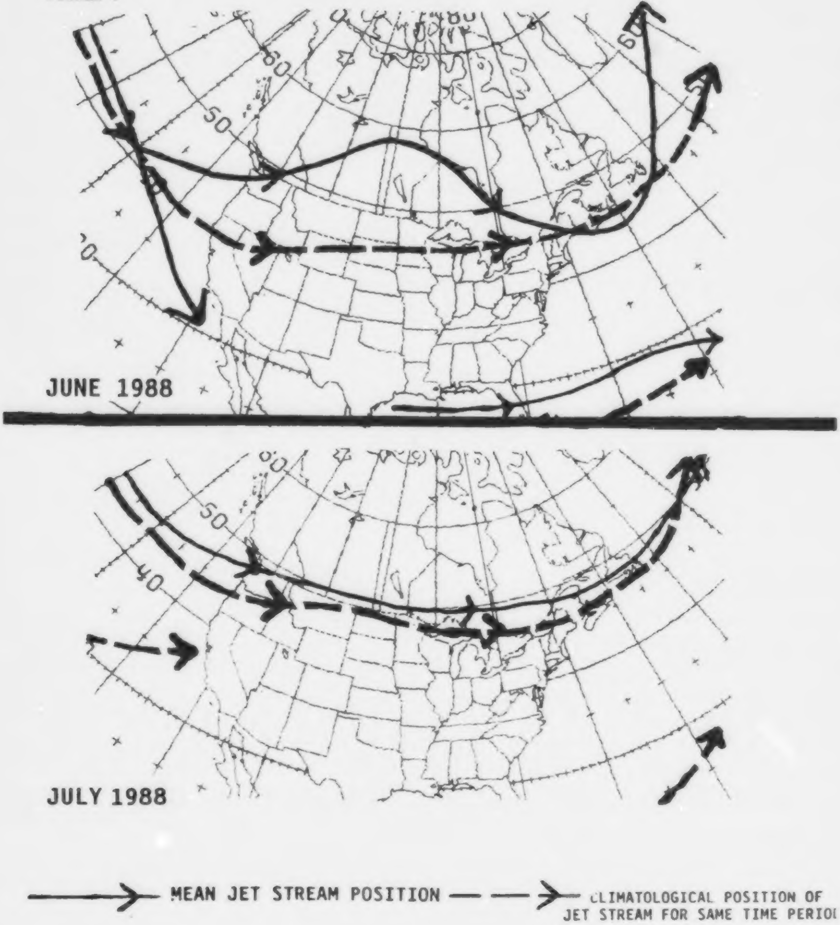
FIGURE 6

APRIL - JUNE PRECIPITATION RANKINGS
(58 YEARS OF RECORD - BY CLIMATE DIVISION)


1931-1988 (58 YEARS)
■
. 2-6 DRIEST .
FINAL NCDC DATA
CLIMATE ANALYSIS CENTER
NMC/NWS/NOAA

MONTHLY JET STREAM POSITIONS

FIGURE 7

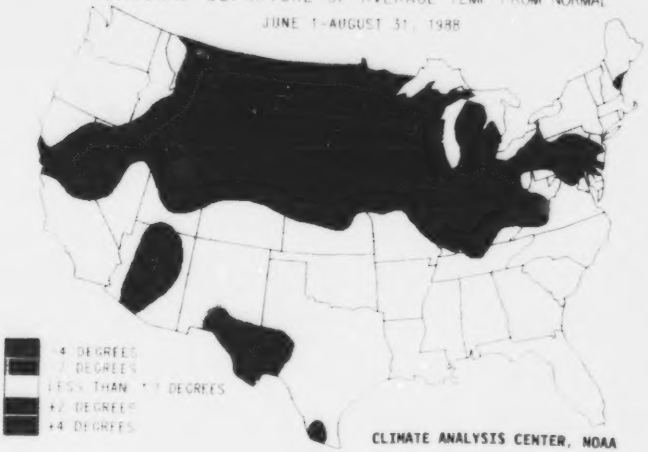

80
60
50
60
JUNE 1988
60
50
40
JULY 1988
MEAN JET STREAM POSITION
CLIMATOLOGICAL POSITION OF JET STREAM FOR SAME TIME PERIOD

CLIMATE ANALYSIS CENTER, NOAA

FIGURE 8

SEASONAL DEPARTURE OF AVERAGE TEMP FROM NORMAL

JUNE 1-AUGUST 31, 1988

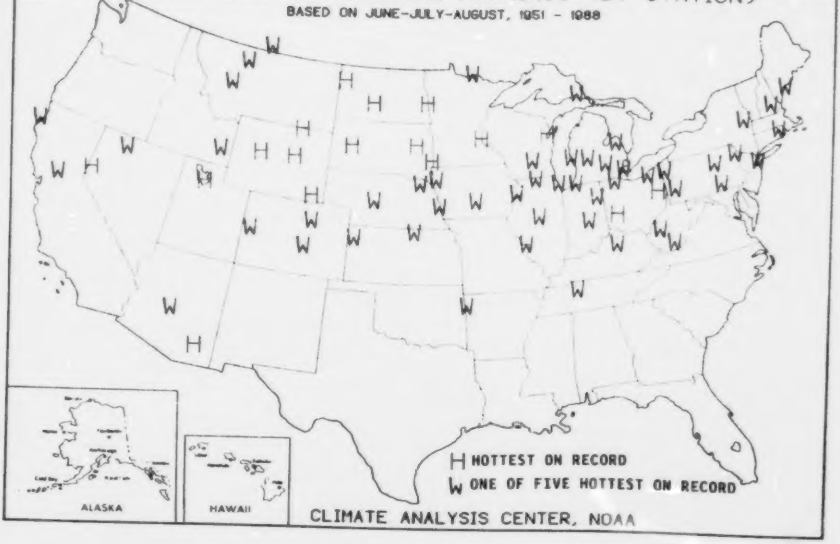

-4 DEGREES
-2 DEGREES
LESS THAN +-2 DEGREES
+2 DEGREES
+4 DEGREES

CLIMATE ANALYSIS CENTER, NOAA

FIGURE 9

SUMMER 1988 TEMPERATURE RANKINGS (BY STATION)

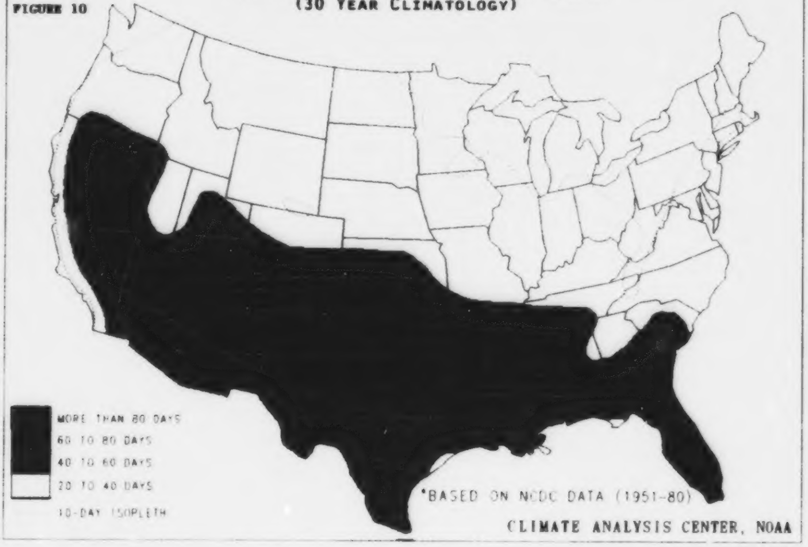
BASED ON JUNE-JULY-AUGUST, 1951 - 1988


ALASKA
HAWAII
H HOTTEST ON RECORD
W ONE OF FIVE HOTTEST ON RECORD

CLIMATE ANALYSIS CENTER, NOAA

NUMBER OF DAYS ≥90°F JUNE - AUGUST
(30 YEAR CLIMATOLOGY)

FIGURE 10

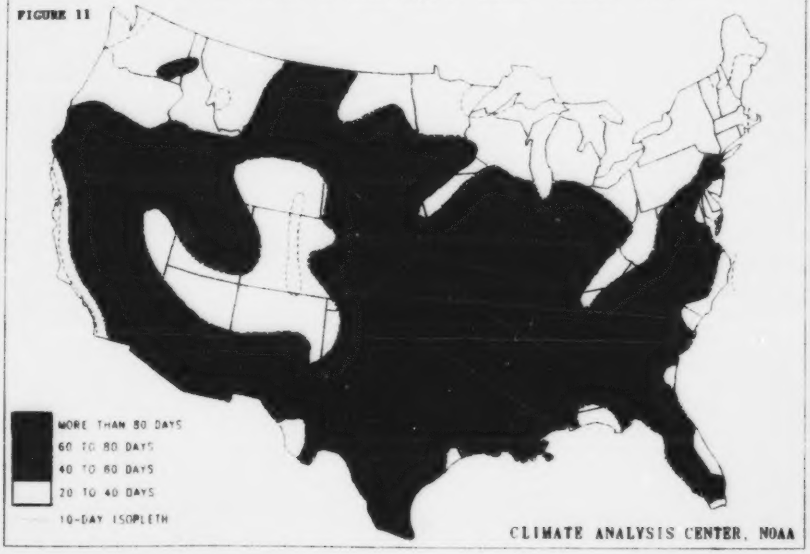

MORE THAN 80 DAYS
60 TO 80 DAYS
40 TO 60 DAYS
20 TO 40 DAYS
10-DAY ISOPLETH

*BASED ON NCDC DATA (1951-80)

CLIMATE ANALYSIS CENTER, NOAA

OBSERVED NUMBER OF DAYS ≥90°F JUNE - AUGUST 1988

FIGURE 11

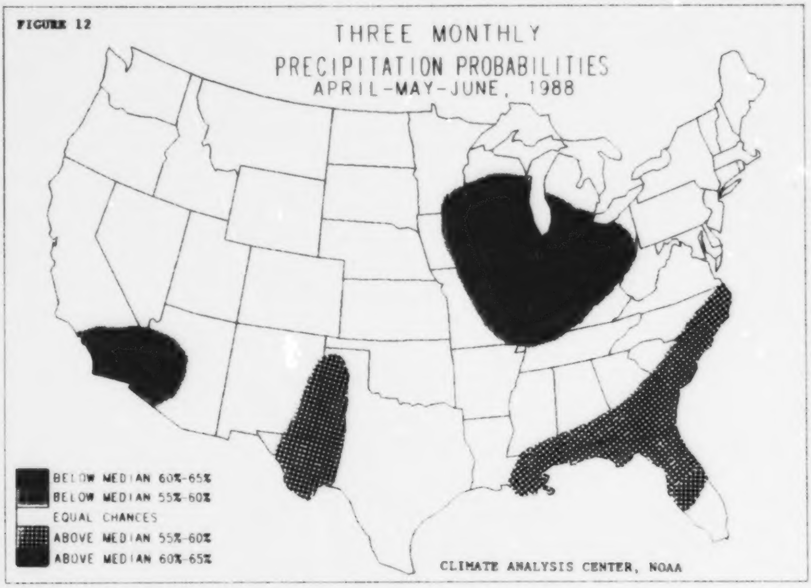

MORE THAN 80 DAYS
60 TO 80 DAYS
40 TO 60 DAYS
20 TO 40 DAYS
10-DAY ISOPLETH

CLIMATE ANALYSIS CENTER, NOAA

FIGURE 12

THREE MONTHLY PRECIPITATION PROBABILITIES

APRIL-MAY-JUNE, 1988


BELOW MEDIAN 60%-65%
BELOW MEDIAN 55%-60%
EQUAL CHANCES
ABOVE MEDIAN 55%-60%
ABOVE MEDIAN 60%-65%

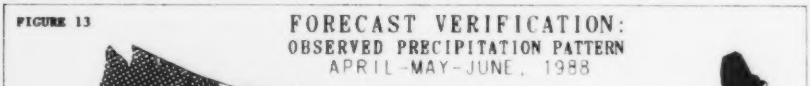
CLIMATE ANALYSIS CENTER, NOAA

FIGURE 13

FORECAST VERIFICATION:

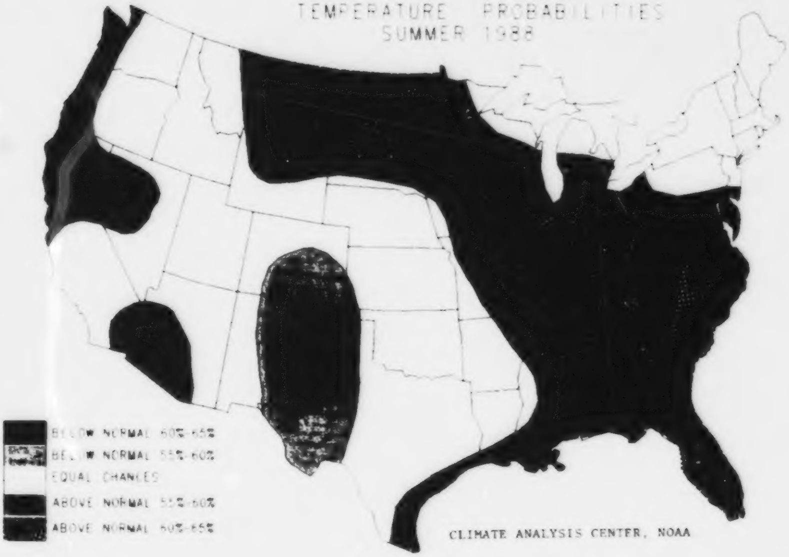
OBSERVED PRECIPITATION PATTERN

APRIL-MAY-JUNE, 1988


BELOW NORMAL
NEAR NORMAL
ABOVE NORMAL

CLIMATE ANALYSIS CENTER, NOAA

FIGURE 14

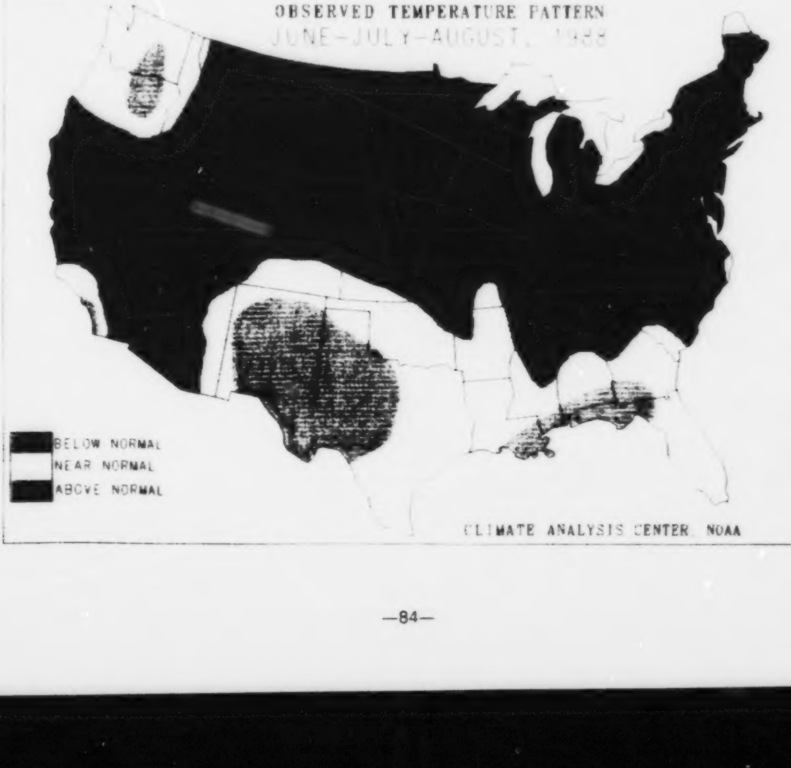


SEASONAL OUTLOOK
TEMPERATURE PROBABILITIES
SUMMER 1988

BELOW NORMAL 60%-65%
BELOW NORMAL 55%-60%
EQUAL CHANCES
ABOVE NORMAL 55%-60%
ABOVE NORMAL 60%-65%

CLIMATE ANALYSIS CENTER, NOAA

FIGURE 15



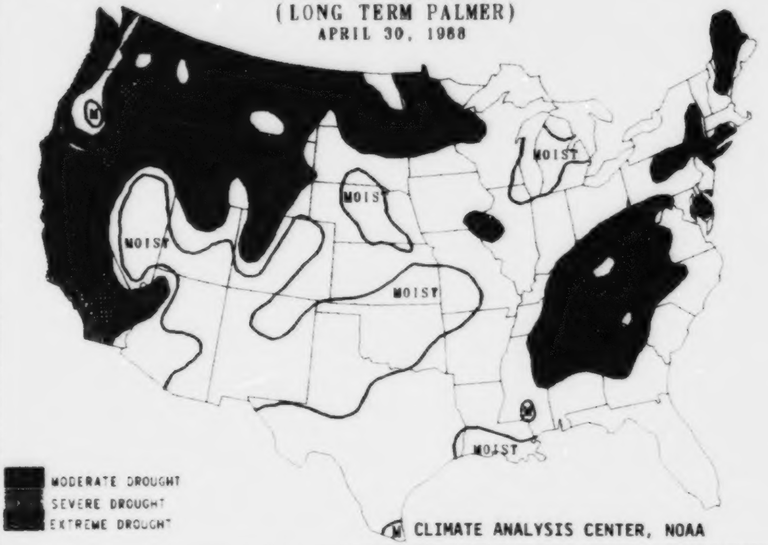
FORECAST VERIFICATION:
OBSERVED TEMPERATURE PATTERN
JUNE-JULY-AUGUST, 1988

BELOW NORMAL
NEAR NORMAL
ABOVE NORMAL

CLIMATE ANALYSIS CENTER, NOAA

FIGURE 16

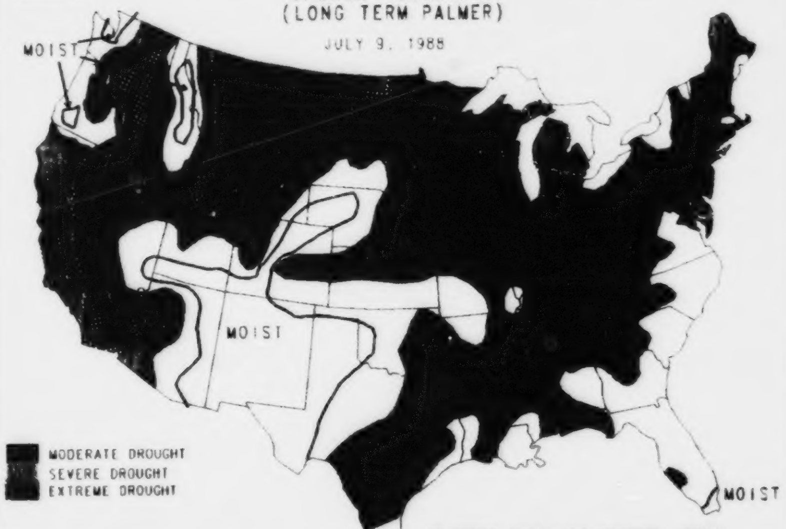
DROUGHT SEVERITY
(LONG TERM PALMER)
APRIL 30, 1988


M
MOIST
MOIST
MOIST
MOIST
MOIST
M
MOIST
MODERATE DROUGHT
SEVERE DROUGHT
EXTREME DROUGHT
M

CLIMATE ANALYSIS CENTER, NOAA

FIGURE 17

DROUGHT SEVERITY
(LONG TERM PALMER)
JULY 9, 1988

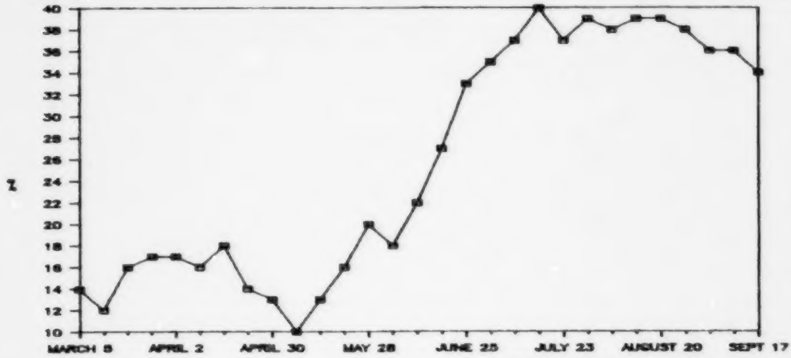

MOIST
MOIST
MOIST
MODERATE DROUGHT
SEVERE DROUGHT
EXTREME DROUGHT

CLIMATE ANALYSIS CENTER, NOAA

FIGURE 18

AREAL PERCENTAGE OF CONTIGUOUS UNITED STATES EXPERIENCING SEVERE OR EXTREME DROUGHT

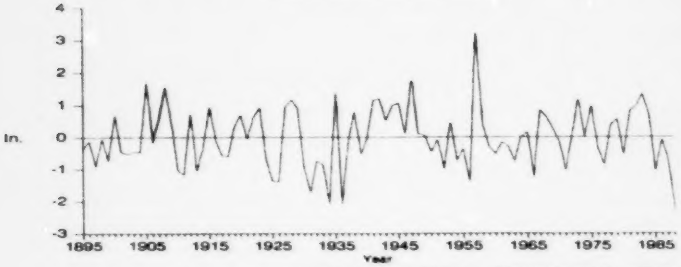
(BASED ON PALMER DROUGHT SEVERITY INDEX ON DATES INDICATED)



CLIMATE ANALYSIS CENTER, NOAA

FIGURE 19 **AREALLY AVERAGED NATIONAL**

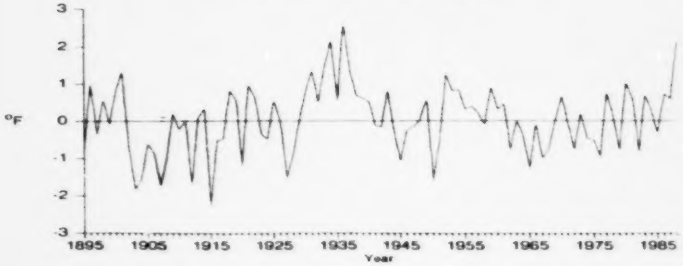
Precipitation Departure, April-June



NATIONAL CLIMATIC DATA CENTER, NOAA

FIGURE 20 **AREALLY AVERAGED NATIONAL**

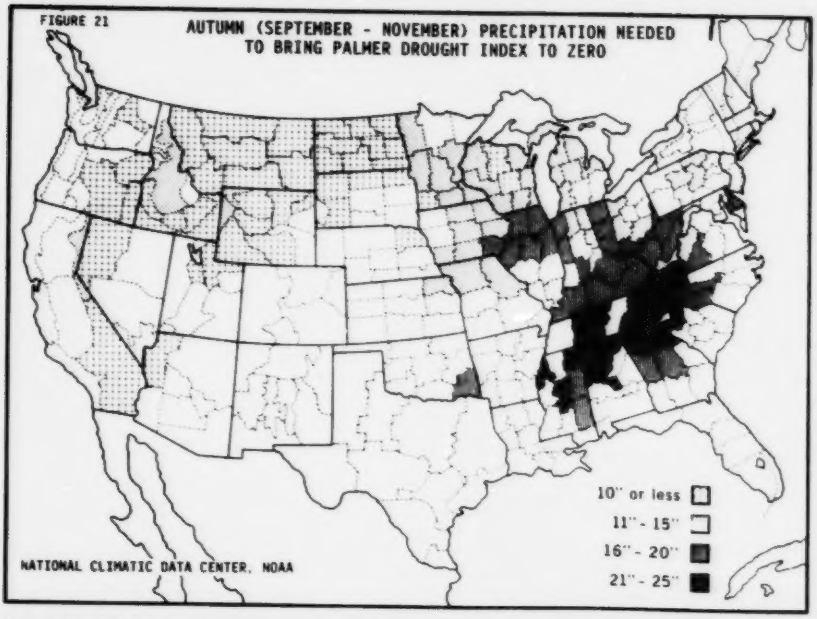
Temperature Departure, June-August



NATIONAL CLIMATIC DATA CENTER, NOAA

FIGURE 21

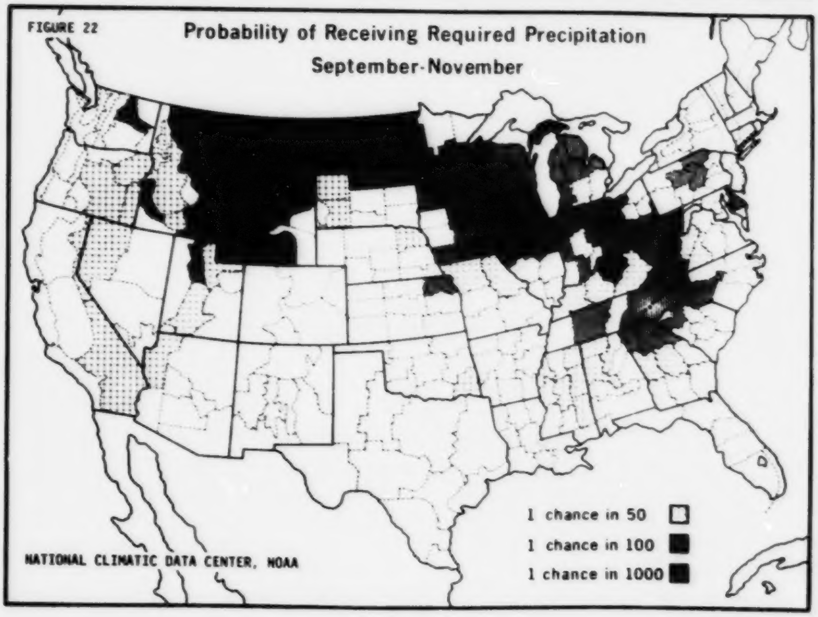
AUTUMN (SEPTEMBER - NOVEMBER) PRECIPITATION NEEDED TO BRING PALMER DROUGHT INDEX TO ZERO


10" or less
11" - 15"
16" - 20"
21" - 25"

NATIONAL CLIMATIC DATA CENTER, NOAA

FIGURE 22

Probability of Receiving Required Precipitation September-November

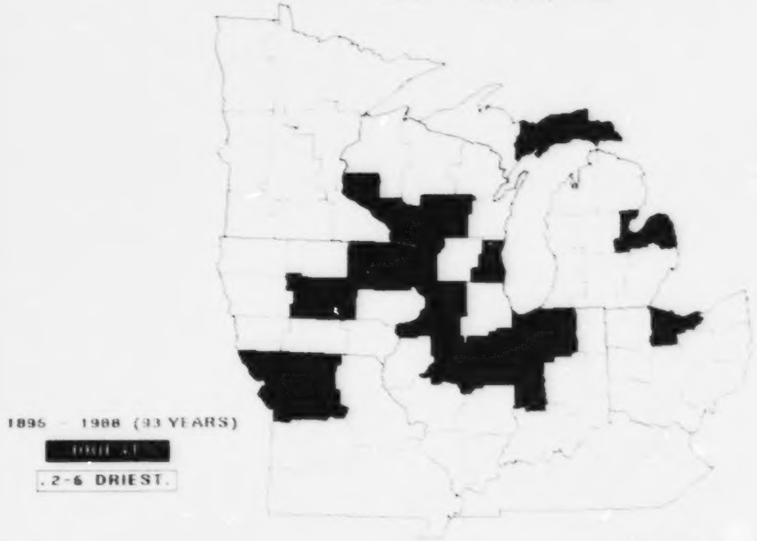

1 chance in 50
1 chance in 100
1 chance in 1000

NATIONAL CLIMATIC DATA CENTER, NOAA

FIGURE 23

PRECIPITATION RANKINGS

APRIL - AUGUST, 1988


1896 - 1988 (93 YEARS)
DRIEST
2-6 DRIEST.

MIDWEST CLIMATE CENTER

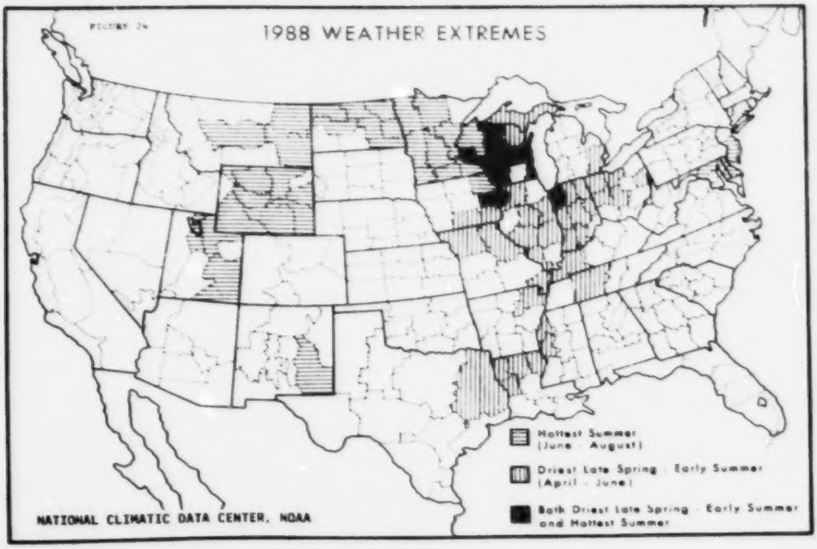


FIGURE 24

1988 WEATHER EXTREMES

▤ Hottest Summer (June - August)
▥ Driest Late Spring - Early Summer (April - June)
■ Both Driest Late Spring - Early Summer and Hottest Summer

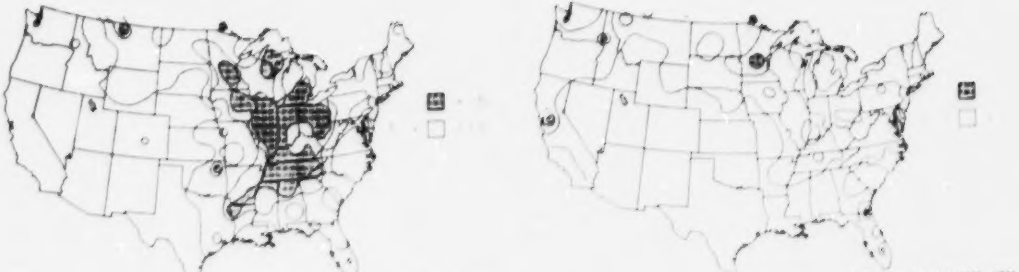
NATIONAL CLIMATIC DATA CENTER, NOAA

HISTORICAL PERSPECTIVE - PRECIPITATION APRIL-JUNE

FIGURE 25

PRECIPITATION PERCENTILES, APRIL - JUNE, 1988

PRECIPITATION PERCENTILES, APRIL - JUNE, 1987

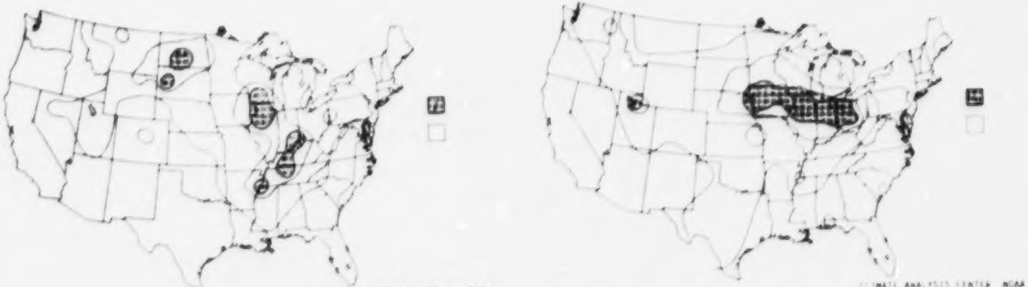


CLIMATE ANALYSIS CENTER, NOAA

CLIMATE ANALYSIS CENTER, NOAA

PRECIPITATION PERCENTILES, APRIL - JUNE, 1936

PRECIPITATION PERCENTILES, APRIL - JUNE, 1934



CLIMATE ANALYSIS CENTER, NOAA

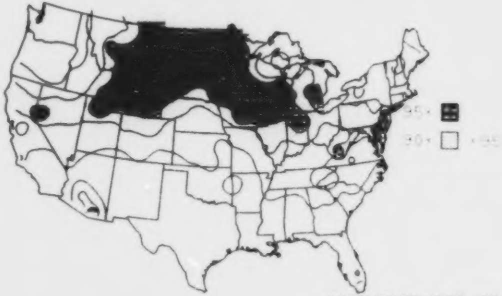
CLIMATE ANALYSIS CENTER, NOAA

PRECIPITATION DEFICIENCY FOR THE APRIL THROUGH JUNE PERIOD EXPRESSED AS A PERCENTILE. THE 5 (10) PERCENTILE REGIONS ARE SHOWN IN DARK (LIGHT) SHADING.

FIGURE 26

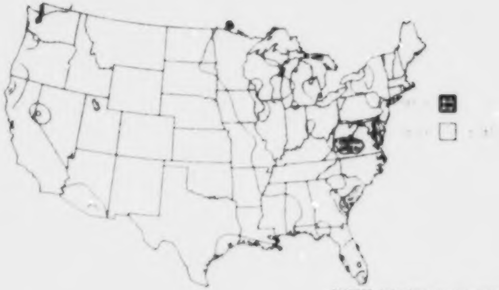
HISTORICAL PERSPECTIVE - TEMPERATURE JUNE-AUGUST

TEMPERATURE PERCENTILES, JUNE - AUGUST, 1988



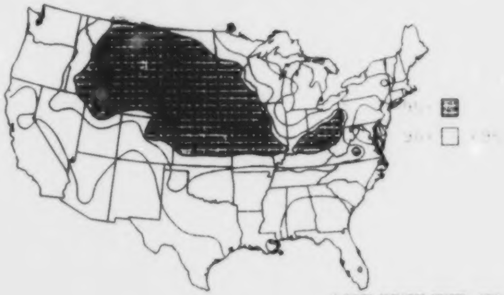
CLIMATE ANALYSIS CENTER, NOAA

TEMPERATURE PERCENTILES, JUNE - AUGUST, 1987



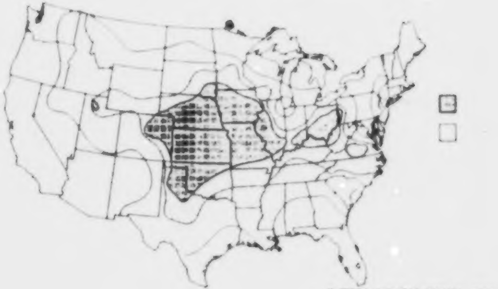
CLIMATE ANALYSIS CENTER, NOAA

TEMPERATURE PERCENTILES, JUNE - AUGUST, 1936



CLIMATE ANALYSIS CENTER, NOAA

TEMPERATURE PERCENTILES, JUNE - AUGUST, 1934

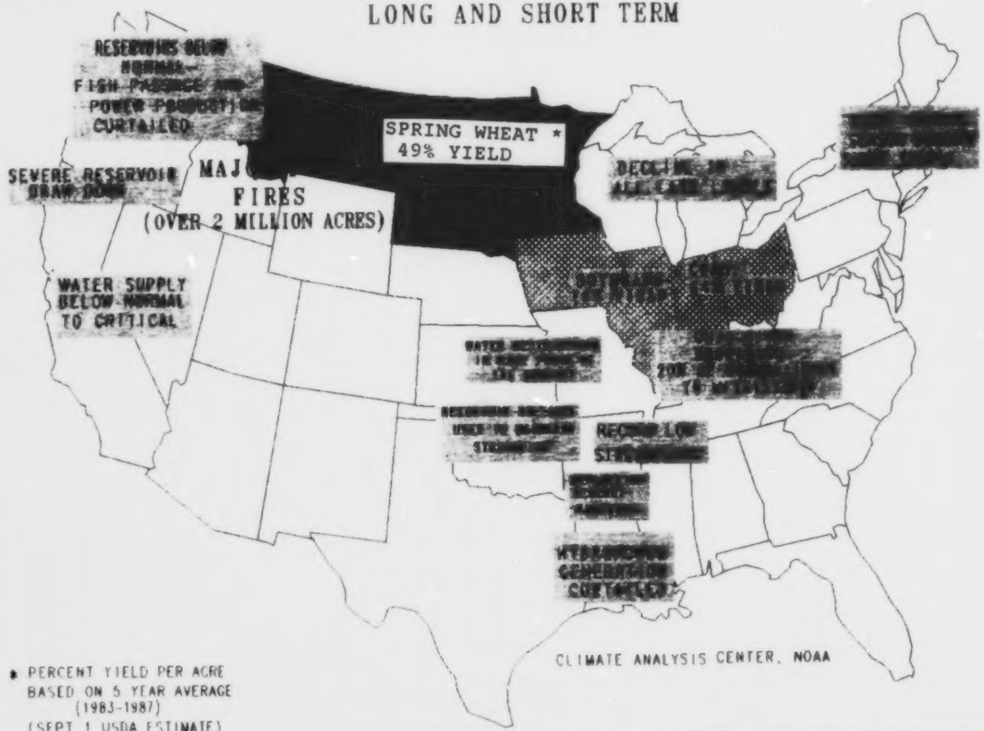


CLIMATE ANALYSIS CENTER, NOAA

TEMPERATURE EXPRESSED AS PERCENTILES FOR THE SUMMER MONTHS. THE 95 (90) PERCENTILE REGIONS ARE SHOWN IN DARK (LIGHT) SHADING.

FIGURE 27

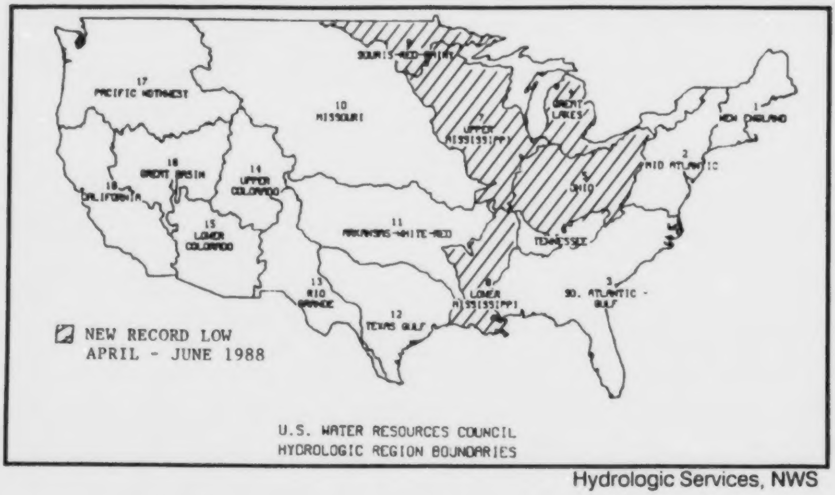
DROUGHT IMPACTS-1988
LONG AND SHORT TERM


RESERVOIRS BELOW NORMAL— FISH PASSAGE AND POWER PRODUCTION CURTAILED
SEVERE RESERVOIR DRAW DOWN
MAJ FIRES (OVER 2 MILLION ACRES)
WATER SUPPLY BELOW NORMAL TO CRITICAL
SPRING WHEAT * 49% YIELD
DECLINE IN ALL LAKE LEVELS
RECORD LOW STREAMFLOW
HYDROPOWER GENERATION CURTAILED

* PERCENT YIELD PER ACRE BASED ON 5 YEAR AVERAGE (1983-1987) (SEPT 1 USDA ESTIMATE)

CLIMATE ANALYSIS CENTER, NOAA

FIGURE 28


17
PACIFIC NORTHWEST
10
MISSOURI
9
SOURIS-RED-RAINY
7
UPPER
MISSISSIPPI
4
GREAT
LAKES
1
NEW ENGLAND
2
MID ATLANTIC
5
OHIO
16
GREAT BASIN
18
CALIFORNIA
14
UPPER
COLORADO
15
LOWER
COLORADO
11
ARKANSAS-WHITE-RED
6
TENNESSEE
13
RIO
GRANDE
12
TEXAS GULF
8
LOWER
MISSISSIPPI
3
SO. ATLANTIC -
GULF
▨ NEW RECORD LOW
APRIL - JUNE 1988
U.S. WATER RESOURCES COUNCIL
HYDROLOGIC REGION BOUNDARIES

Hydrologic Services, NWS

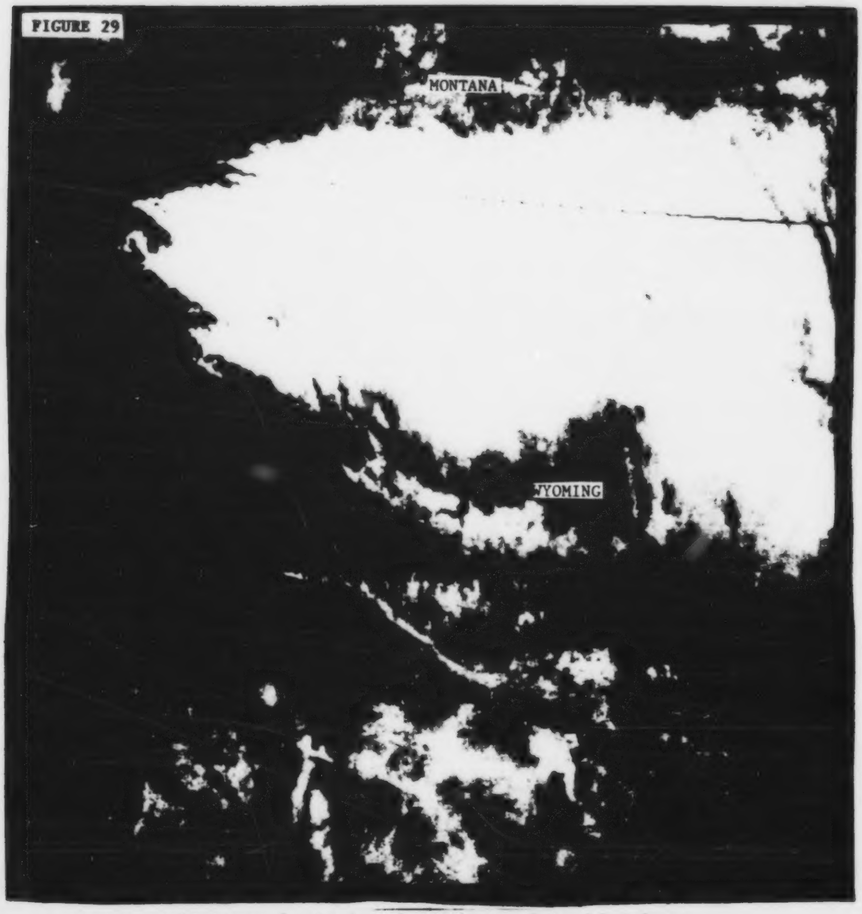
PRECIPITATION AVERAGES FOR HYDROLOGIC REGIONS

REGION	SEASONAL AVERAGES	HISTORICAL AVERAGE (1931-1987)	PERCENT OF AVERAGE	PROBABILITY OF LESS	PREVIOUS RECORD LOW/YEAR
EAST OF CONT. DIVIDE -- (Spring) Season averages, April thru June '88					
1	7.88	11.00	72	14%	6.49 / 1965
2	10.35	11.02	94	44%	6.54 / 1965
3	8.82	12.83	69	3%	7.95 / 1986
4	* 3.88	9.52	41	1%	5.90 / 1934
5	* 6.15	12.05	51	1%	7.00 / 1936
6	8.39	12.87	65	3%	8.14 / 1941
7	* 4.13	11.11	37	1%	5.91 / 1934
8	* 7.16	13.98	51	1%	7.50 / 1931
9	* 2.64	7.69	34	1%	3.64 / 1980
10	5.10	8.33	61	5%	4.84 / 1936
11	7.75	11.82	66	5%	7.03 / 1936
12	6.20	9.85	63	8%	4.98 / 1984
13	2.91	2.57	113	63%	0.98 / 1974
WEST OF CONT. DIVIDE -- (Winter) Season averages, Nov. '87 thru Apr. '88					
14	6.37	5.92	# 108	62%	2.23 / 1976
15	7.32	5.88	# 125	74%	1.92 / 1971
16	6.43	6.07	# 106	57%	1.93 / 1966
17	17.72	20.96	# 85	16%	9.34 / 1976
18	14.24	19.98	# 71	19%	6.77 / 1976

* = New Record Low

# = Minimal high elevation snow data used in computing averages. (Generally low snow pack last winter influencing lower streamflow in many areas than these averages may indicate.)

FIGURE 29


MONTANA
WYOMING

NOAA - 9 AVHRR image of smoke plumes from Yellowstone National Park forest fires, September 7, 1988

FIGURE 30

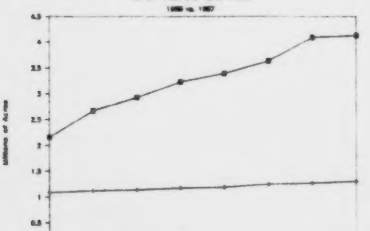


FIGURE 31

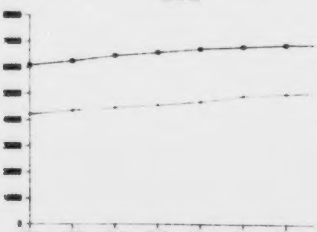
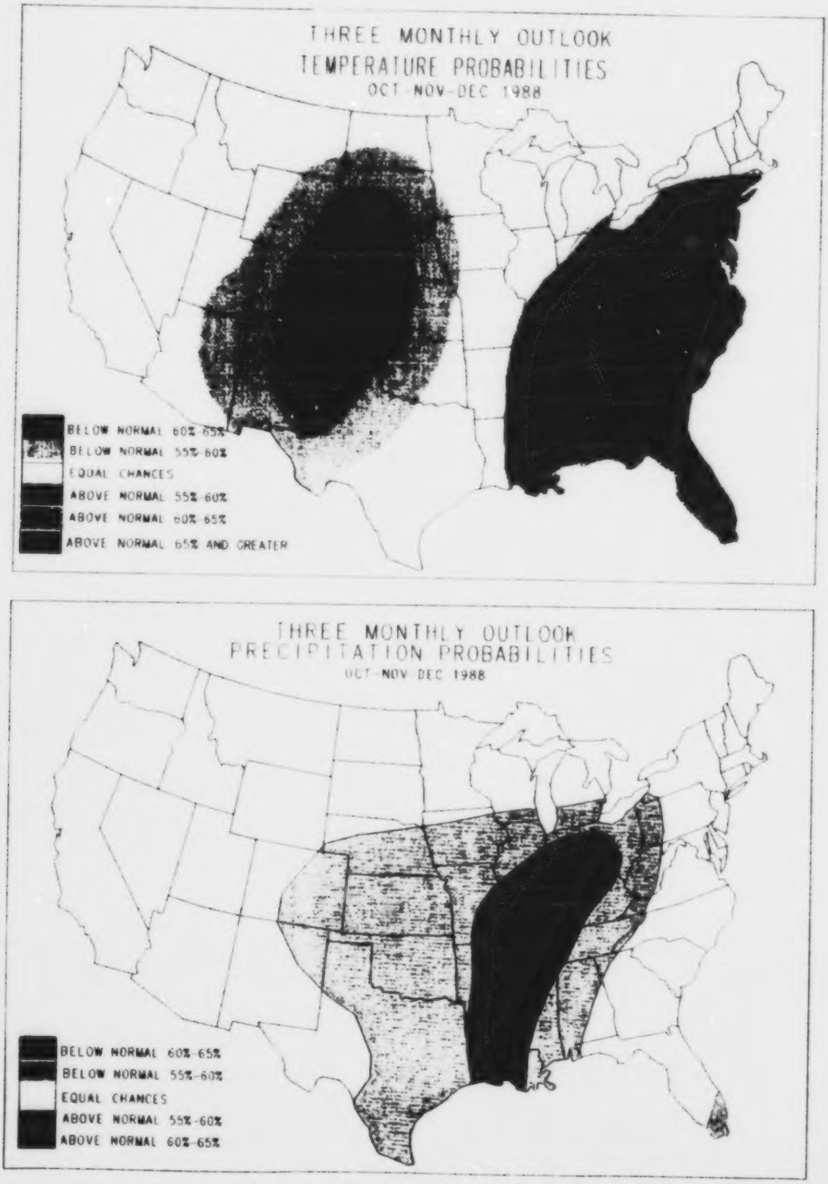


FIGURE 32

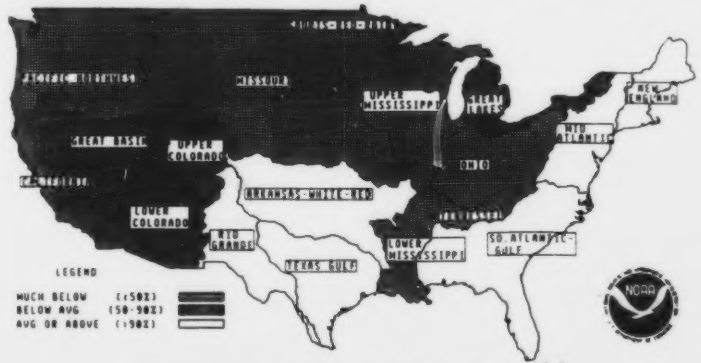

THREE MONTHLY OUTLOOK
TEMPERATURE PROBABILITIES
OCT-NOV-DEC 1988
BELOW NORMAL 60%-65%
BELOW NORMAL 55%-60%
EQUAL CHANCES
ABOVE NORMAL 55%-60%
ABOVE NORMAL 60%-65%
ABOVE NORMAL 65% AND GREATER
THREE MONTHLY OUTLOOK
PRECIPITATION PROBABILITIES
OCT-NOV-DEC 1988
BELOW NORMAL 60%-65%
BELOW NORMAL 55%-60%
EQUAL CHANCES
ABOVE NORMAL 55%-60%
ABOVE NORMAL 60%-65%

CLIMATE ANALYSIS CENTER, NOAA

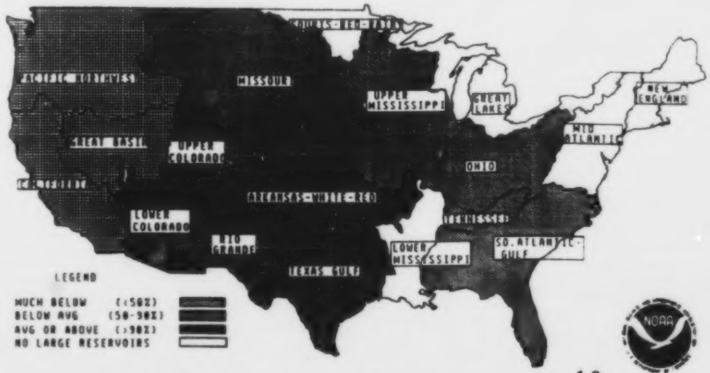
FIGURE 33

FALL STREAMFLOW & RESERVOIR STORAGE OUTLOOKS

BY U.S. WATER RESOURCES COUNCIL HYDROLOGIC REGIONS


SOURIS-RED-RAINY
PACIFIC NORTHWEST
MISSOURI
UPPER MISSISSIPPI
GREAT LAKES
NEW ENGLAND
MID ATLANTIC
GREAT BASIN
UPPER COLORADO
OHIO
CALIFORNIA
ARKANSAS-WHITE-RED
LOWER COLORADO
TENNESSEE
RIO GRANDE
LOWER MISSISSIPPI
SO. ATLANTIC-GULF
TEXAS GULF
LEGEND
MUCH BELOW (<50%)
BELOW AVG (50-90%)
AVG OR ABOVE (>90%)
NOAA

STREAMFLOW OUTLOOK FOR FALL, 1988 1,2


SOURIS-RED-RAINY
PACIFIC NORTHWEST
MISSOURI
UPPER MISSISSIPPI
GREAT LAKES
NEW ENGLAND
MID ATLANTIC
GREAT BASIN
UPPER COLORADO
OHIO
CALIFORNIA
ARKANSAS-WHITE-RED
TENNESSEE
LOWER COLORADO
RIO GRANDE
LOWER MISSISSIPPI
SO. ATLANTIC-GULF
TEXAS GULF
LEGEND
MUCH BELOW (<50%)
BELOW AVG (50-90%)
AVG OR ABOVE (>90%)
NO LARGE RESERVOIRS
NOAA

RESEVOIR STORAGE OUTLOOK FOR FALL, 1988 1,2

1. CATEGORY REFLECTS THE MEAN CONDITION FOR EACH REGION.
2. ASSUMES INSUFFICIENT RAINFALL TO PRODUCE SIGNIFICANT RUNOFF.

Hydrologic Services, NWS

DROUGHT MONITORING, DETECTION AND EARLY WARNING FROM A HYDROLOGIC PERSPECTIVE

by
A.A. Warkentin
Water Resources Branch
Manitoba Department of Natural Resources

1. MEANING OF HYDROLOGIC DROUGHT

Many definitions of drought have been formulated. It is generally defined as a period of dry weather of sufficient duration to cause serious and unusual water supply shortages. Such shortages may develop in reservoirs, lakes and streams (surface water) and in the soil, subsoil or groundwater (sub-surface water). Drought usually has direct consequences such as crop failure, severe forest fires, shortages of electrical energy, a lack of suitable habitat for waterfowl and fish and a lack of water for consumptive use by humans and animals. The consequences can be devastating, depending on the intensity and duration of the drought.

Hydrologic drought in this paper is considered to be that component of drought relating to water shortages in reservoirs, lakes, streams and groundwater.

2. SEVERITY OF HYDROLOGIC DROUGHT

Methodologies have been developed to define the occurrence and severity of drought. A well known procedure is that of the Palmer Drought Severity Index (PDSI)[1]. PDSI has been primarily used as an indicator of the severity of agricultural drought and has not been widely used for hydrologic drought. The representativeness of PDSI as an indicator of hydrologic drought has been questioned. W.M. Alley, a hydrologist with the United States Geological Survey in Virginia has compared streamflow and groundwater data to PDSI for the State of new Jersey [2]. It was found that during long, sustained wet or dry periods, there was a good relationship. However, during times of change from wet months to dry months PDSI overestimated the severity of groundwater drought and during a change from dry months to wet months it generally overestimated the severity of surface water drought. I have found that PDSI values do not relate well to the antecedent precipitation index (API) parameter commonly used in index models for runoff forecasting.

In my view it is unnecessary to compute drought severity indicators for hydrologic drought. It is more advantageous to simply examine the state of reservoirs, lakes, streams and groundwater levels as they relate to the average values and previous extreme recorded values. If sufficient historic data is available, it is easy to evaluate and express the extremity of a particular situation in terms of percentiles. For example, one might do a duration analysis of September river flows for the Red

River at Emerson as shown on Figure 1. This shows that the September flow at Emerson was close to the 10th percentile for the period from 1912 to 1988. Since 1940 only one other year (1961) had flows this low in September.

Expressions of drought severity are of little use unless they can be related to risk and consequence. In agriculture PDSI must be related to the wilting point of plants and likelihood of damage to crops. In hydrology indications of unusually low water supplies evoke the need to project water supplies and demands to determine the likelihood of water shortages developing within certain time frames. To determine the risk it is necessary to assume various scenarios with respect to meteorological inputs, thus making this a probabilistic exercise.

3. STATUS OF 1988 DROUGHT IN MANITOBA

In southern Manitoba the 1987-88 drought has been intense with respect to smaller streams, dugouts, sloughs, shallow lakes and marginal aquifers, particularly in the Red River Valley and in southwestern Manitoba. Most small and moderate size streams have dried up, except where they are fed by reservoirs or springs. Where spring pumping was unsuccessful, dugouts and ponds are in short supply or have dried up. Even Whitewater Lake, normally a 78 km^2 (30 mi^2) lake without an outlet has dried up. The lake had not dried up since the 1930's. Water supplies in some marginal aquifers have declined to near record lows, necessitating improvement or relocation of wells.

As of early October, water supplies were still quite adequate in Provincial reservoirs but there was serious concern for 1989. A good recharge will be needed next spring.

Water shortages had not yet occurred on major streams such as the Red River, the Assiniboine River or the Souris River, mainly due to releases of water from storage reservoirs. However, September flows on the Red River and the Souris River were among the lowest on record. There were serious water shortages this summer with respect to hydroelectric power production on the Winnipeg River, the Saskatchewan River and the Nelson River where record low summer flows were observed. Lake Winnipeg levels were also unusually low although outlet controls prevented levels from falling to extremes.

Hydrologic drought conditions in Manitoba in 1988 resemble those of 1961 and, to some extent, those of 1977. Both the 1961 and 1988 droughts were preceded by below average runoff during at least four of the six years preceding the drought years. Such dry antecedent conditions play an important role in reducing water storages in advance and thus worsening water shortages during extreme meteorological drought years.

4. DROUGHT MONITORING

Data networks operated by Manitoba and Canada on an ongoing basis are used for drought monitoring. These include the real-time Hydrometric Network operated by Water Survey of Canada (some of these stations are cost-shared by Manitoba) and shown on Figure 2, the Soil Moisture Network operated by Manitoba (Figure 3), the Snow Survey Network operated by Manitoba (Figure 4), the Precipitation network operated by the Atmospheric Environment Service and the Groundwater Network operated by Manitoba (Figure 5). The latter shows only the number of stations per sub-basin since the network is too dense to depict easily.

Hydrometric data for real-time stations are obtained on a daily or hourly basis. Soil moisture surveys are done near freeze-up each fall and snow surveys are done in February and in March. Precipitation data is obtained daily from AES and isohyetal maps for storms, months and seasons are drawn. A weather radar is used to help track convective rainstorms. A precipitation map for the period from November, 1987 to March, 1988 is shown on Figure 6. A map of percent of normal precipitation for the period from April to September, 1988, is shown on Figure 7.

Manitoba also collects water level data for Provincial reservoirs not equipped with electronic real-time data systems. Such data are normally sent in weekly by mail. The Provincial reservoir network is shown on Figure 8.

Information on river flows and reservoir/lake levels is distributed weekly to a large number of government officials, municipalities, towns and private individuals. A sample sheet for lakes in southern Manitoba is shown on Figure 9.

Manitoba is also involved in federal-provincial experimental programs to obtain better information on soil moisture and snow cover in near-real-time using airborne and spaceborne techniques.

While drought monitoring and the assessment of drought severity is mainly done through close scrutiny of actual water levels and storages and of projected water supplies and uses, precipitation data is also used to provide information on the relative intensity and spacial characteristics of drought. A table comparing fall, winter and summer precipitation for southern Manitoba from 1932 to 1988 is shown on Figure 10. The years are ordered from the least to the greatest winter precipitation. This shows the 1988 drought to be one of the severest on record from a climatological standpoint. Guezen and Raddatz [3] of AES suggest that the current decade may rival the "Dirty Thirties" as the driest period in Canada's history.

5. TEMPORAL ASPECTS OF HYDROLOGIC DROUGHT

Hydrologic drought is slower to develop than agricultural drought due to the larger water storages involved. The root zone for most prairie crops is quite shallow and may be dried out after a month or two of dry weather during the active growing season. In forestry, a month of hot, dry weather can shift the Fire Index from low to extreme. In hydrology, however, there is greater inertia to change because water storages are larger relative to the components of the water cycle.

Smaller streams (drainage areas under several hundred square kilometres) are generally the first to experience hydrologic drought. Such streams normally dry up every summer unless they are fed by springs. However, after a dry winter such streams often will not flow for the entire year.

Medium-sized streams, dugouts and sloughs are usually next to experience hydrologic drought. During 1988 the Qu'Appelle River at Welby, the Pembina River at Windygates and the Souris River at Wawanesa dried up completely. Dugouts and sloughs were generally dry unless they had been replenished by pumping during the spring.

Large rivers, shallow lakes with small drainage areas and marginal groundwater aquifers tend to experience hydrologic drought next if meteorological drought persists. Large rivers tend to withstand drought longer than smaller rivers because the odds are better that some portion of a large watershed will receive substantial precipitation. This may not be the case for widespread, intense meteorological drought. During September, 1988, flows on the Red River were nearing the lowest on record resulting in fears of winter water supply shortages for towns along the River in Manitoba. An example of a shallow lake with a small drainage area is Whitewater Lake in southwestern Manitoba. It dried up in June, 1988, the first time since the mid 1930's. Marginal shallow aquifers were also becoming dewatered in 1988.

Reservoirs and lakes with small drainage areas are usually next to experience hydrologic drought. Reservoirs are generally designed to withstand an intense two year dry cycle. Manitoba reservoirs all contain sufficient water supplies to last well into 1989. However, if there is little recharge next spring, some reservoirs could be exhausted by late 1989.

Reservoirs and lakes with large drainage areas tend to be the most resistant to drought, but if the meteorological drought is widespread and intense, they may experience drought coincident with that of large rivers. Manitoba has many groundwater aquifers which may be considered as groundwater drought proof [3]. Water shortages for specific wells in these aquifers are usually due to improper well design. It is possible that even these aquifers could be dewatered by a long, intense meteorological drought, but such a drought is unlikely to happen unless there is a substantial change in the climate.

6. SPATIAL ASPECTS OF HYDROLOGIC DROUGHT

Hydrologic drought may be quite discontinuous over relatively short distances due to the occasional random persistence of storm tracks. An example is the spring of 1988 where large portions of southern Manitoba and Saskatchewan received less than 50 percent of normal precipitation while a fairly large area centred over Swan River, Manitoba, received over 200 percent of normal. The heavy spring rain in the Swan River area prevented hydrologic drought in that region during the summer of 1988. Manitoba's largest man-made reservoir, the Shellmouth Reservoir on the upper Assiniboine River is located in this heavy spring rain area. Despite meteorological drought and above average outflows this summer, the Reservoir was still at its normal level in late September, 1988, as shown on Figure 11. Meanwhile in the driest portions of the Red River Valley there was little spring recharge and reservoir levels began to plummet by May, 1988. An example is Morden Reservoir, as shown on Figure 12.

Notwithstanding the odd exception such as the Swan River area, meteorological drought was widespread in 1988, enveloping most of Canada and the United States. In many areas relatively dry conditions had persisted since 1980. This culminated in some rather severe hydrologic drought in many areas. Hydrologic drought had progressed to the point where large rivers such as the Nelson River (Manitoba), the Mississippi River (Mississippi), the Columbia River (Oregon) experienced record low flows during the summer of 1988.

A spatial aspect which is of great importance to hydrologic drought of storage reservoirs is that of drainage area. A reservoir with a large drainage area relative to its consumptive uses has a much better chance of withstanding drought. An example is Stephenfield Reservoir and Morden Reservoir, located only 55 kilometres apart in the Red River Valley. The storage capacities are about the same, but Stephenfield has 10 times the drainage area of Morden Reservoir. During dry springs such as in 1988 runoff depths are minimal. Because of the larger drainage area Stephenfield filled but Morden did not. The differences in storage could become remarkable after a few consecutive dry years.

7. ECONOMIC IMPLICATIONS OF HYDROLOGIC DROUGHT

Preliminary estimates of Manitoba costs and loss of revenue attributable to the 1987-88 drought are shown on Figure 13. The severest impact was on hydroelectric power generation. Manitoba Hydro is projecting a deficit of 60 million dollars for 1988. Abnormal costs of fighting forest fires and of forest restoration, including damage to tree nurseries amounted to about eight million dollars. Drought mitigation measures implemented specifically in response to this drought amounted to about 3.5 million dollars for PFRA and 2.3 million dollars for the Manitoba Water Services Board. These costs were mainly for capital works. Costs incurred by the Manitoba Department of Natural Resources in addition to forest related costs amounted to 2.8 million dollars. These costs included removal of soil from drains and roadside ditches and a variety of other actions such as transportation of haying equipment to remote marshes.

There were also high costs to the private sector and individuals for which dollar figures are not readily available. Costs of hydrologic drought to fisheries, wildlife and waterfowl were likely substantial but were not readily available.

The costs associated with the 1988 hydrologic drought will likely continue to rise even if precipitation reverts to normal. This is due to the fact that winter is approaching and, therefore, hydrologic drought is unlikely to end before the spring of 1989 at the earliest.

8. EARLY WARNING AND DROUGHT MANAGEMENT

Costs and inconvenience related to hydrologic drought can be reduced considerably if there is advance warning of drought. With notification, reservoirs and lakes with outlet controls can be operated so as to maximize the benefit of the available water supplies. For example the Shellmouth Reservoir was operated in an unusual fashion in 1988 as a result of drought warning. Less water was released during the spring so that sufficient supplies would be available to augment Assiniboine River flows throughout the summer. As a result, over 90 percent of the flow on the Assiniboine River at Brandon this summer was composed of releases from the Reservoir. This facilitated thermoelectric power generation at Manitoba Hydro's Brandon plant and prevented a serious deterioration of water quality along the Assiniboine River and along the Red River from Winnipeg to Selkirk. Early warning of hydrologic drought also enables agencies and private individuals to plan strategies, purchase or move equipment, etc., and be ready to implement drought mitigation measures when they are needed.

Accurate early warning of hydrologic drought is difficult to provide since precipitation cannot be accurately predicted months into the future. Nevertheless water supply forecasts based on soil moisture, pothole storage, snow cover and weather contingencies are very much sought after. An example of this type of early warning prepared by our Branch in February and in March is shown on Figure 14.

Spring runoff forecasts are extremely important for water management because 80 to 90 percent of annual runoff in agricultural regions occurs during the spring. During dry years, every effort must therefore be made to capture and store runoff waters during the spring period.

For accurate water supply forecasting it is essential to have good estimates of the fall soil moisture and the winter snowpack since these factors are dominant in determining spring runoff volumes. Precipitation from September through to the following April is highly significant in determining annual surface water recharge. This is demonstrated on Figure 15 from

Sturgeon Creek, a small watershed just northwest of Winnipeg. Runoff on this Creek was 13 times greater in 1979 than in 1977, while annual precipitation in 1979 was less than in 1977. The reason for the much higher runoff in 1979 was the time distribution of precipitation during the water years. Precipitation for September, 1978 to April, 1979, was 3.8 times that for the same period from 1976 to 1977.

While water supply forecasts based on fall and winter precipitation are highly useful for water management and hydrologic drought mitigation, they are not reliable beyond several months due to unknowns in future precipitation. Runoff forecasts must be based on some assumptions for future precipitation, such as the lower decile, median or upper decile conditions. These conditions are computed from past weather records. There could be serious errors in statistical precipitation estimates if unusual and persistent weather patterns develop or if there is significant climatic change. Climatic change and the possibility of longer, more intense droughts than we have seen in the past also raise questions about design criteria for water storage reservoirs. Perhaps they need to be designed to withstand a drought in excess of two years in duration. Hydrologic drought management would be well served by a better knowledge of unusual weather cycles and the implications of climatic change on precipitation evapotranspiration.

LITERATURE CITED

1.Palmer, W.C., 1965. Meteorologic Drought. U.S. Weather Bureau, Research Paper No.1 45.

2.Alley, W.M., 1985. The Palmer Drought Severity Index as a Measure of Hydrologic Drought. Water Resources Bulletin, AWRA, Volume 21, No. 1.

3.Guezen, T.B., and Raddatz, R.L., 1988. The Prairie Drought of 1988: A Synoptic Overview of Temperature and Precipitation Patterns.

4.Rutulis, M., 1987.
Groundwater Drought Sensitivity of Southern Manitoba. Canadian Water Resources Association, 40th Annual Conference.

Figure 1

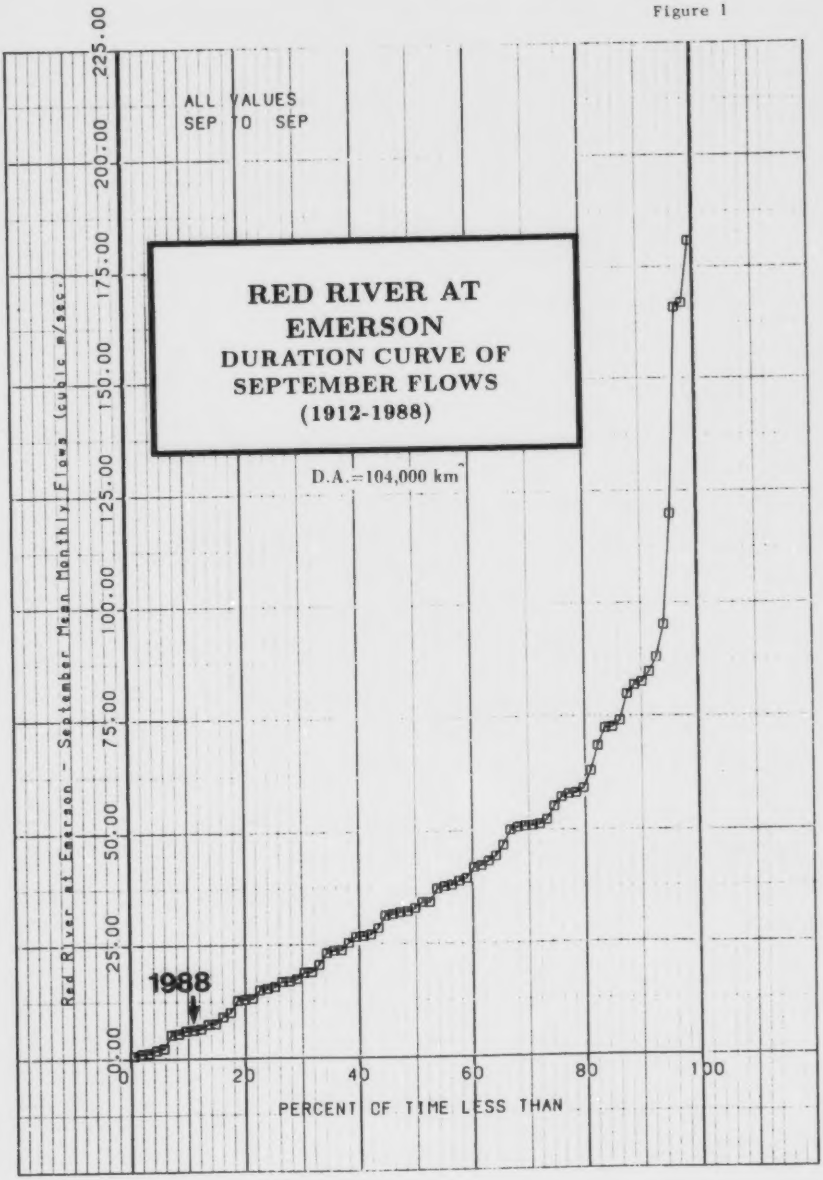
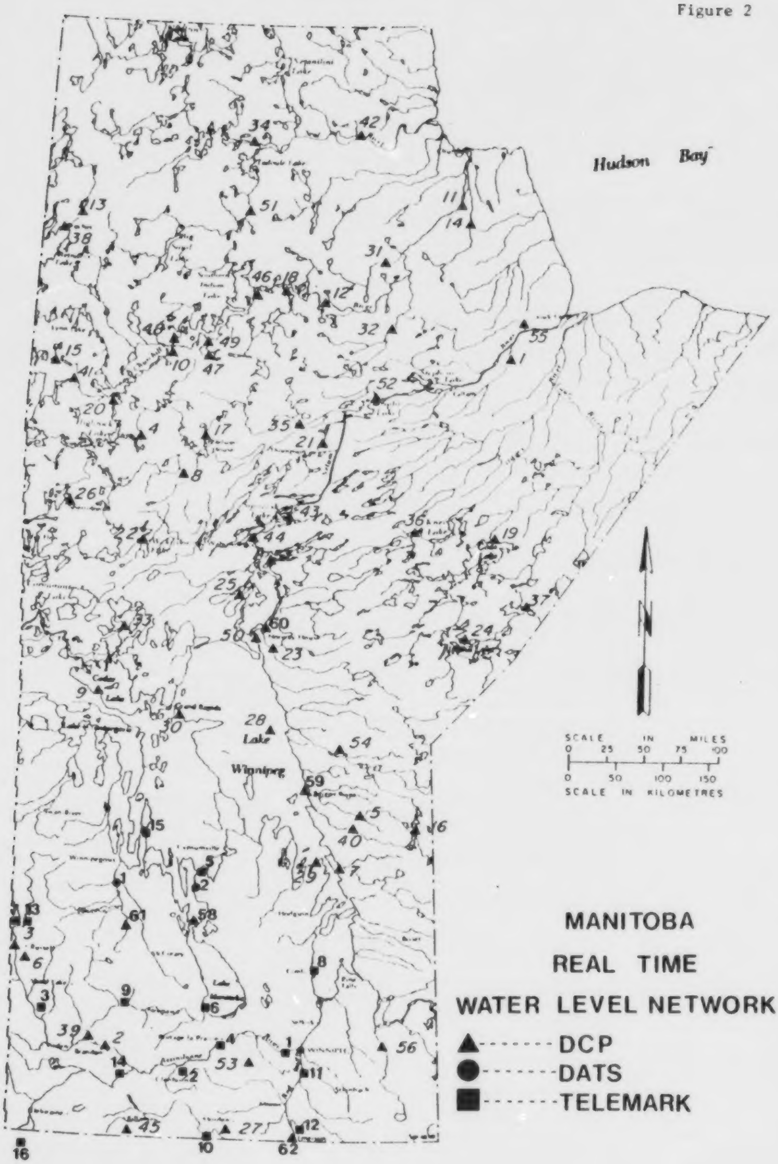
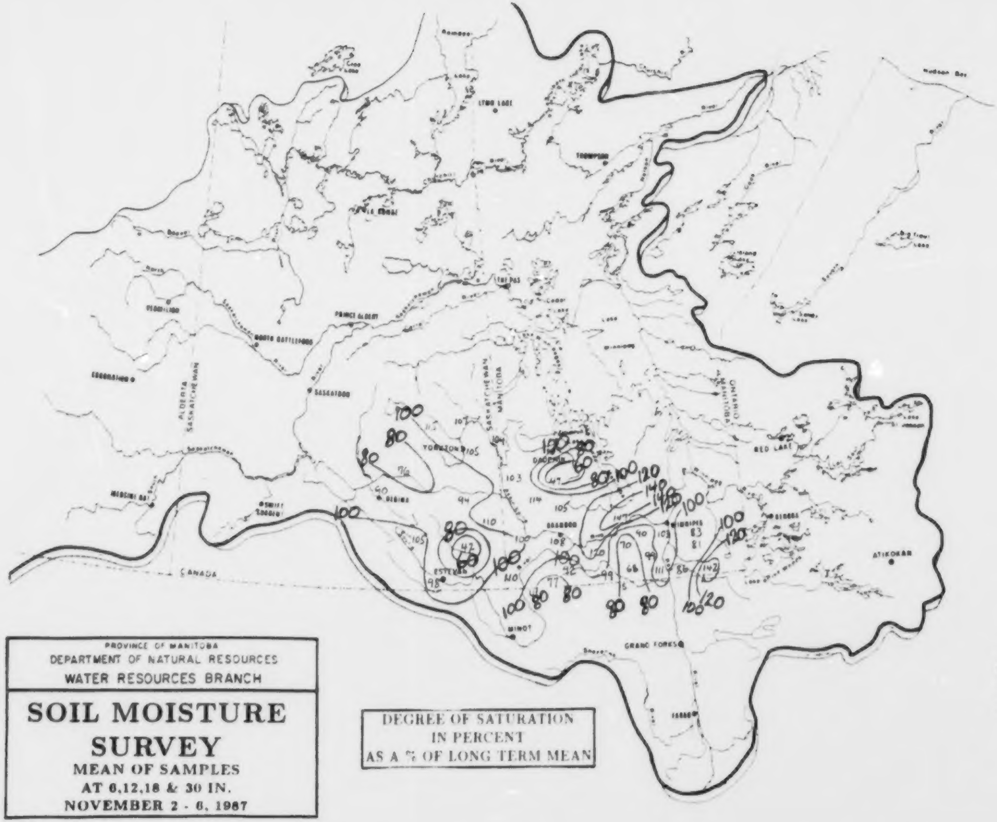

ALL VALUES
SEP TO SEP
RED RIVER AT
EMERSON
DURATION CURVE OF
SEPTEMBER FLOWS
(1912-1988)
D.A.=104,000 km^
1988
Red River at Emerson - September Mean Monthly Flows (cubic m/sec.)
225.00
200.00
175.00
150.00
125.00
100.00
75.00
50.00
25.00
0.00
0
20
40
60
80
100
PERCENT OF TIME LESS THAN

Figure 2


Hudson Bay
Lake Winnipeg
SCALE IN MILES
0 25 50 75 100
0 50 100 150
SCALE IN KILOMETRES
▲------DCP
●------DATS
■------TELEMARK

MANITOBA
REAL TIME
WATER LEVEL NETWORK

Figure 3



Hudson Bay
Lynn Lake
Thompson
The Pas
Prince Albert
North Battleford
Saskatoon
Lloydminster
Edmonton
Medicine Hat
Swift Current
Regina
Yorkton
Dauphin
Brandon
Winnipeg
Estevan
Minot
Grand Forks
Fargo
Red Lake
Kenora
Atikokan
ALBERTA
SASKATCHEWAN
MANITOBA
ONTARIO
CANADA
100
80
120
140
60

PROVINCE OF MANITOBA
DEPARTMENT OF NATURAL RESOURCES
WATER RESOURCES BRANCH

SOIL MOISTURE SURVEY
MEAN OF SAMPLES
AT 6,12,18 & 30 IN.
NOVEMBER 2 - 6, 1987

DEGREE OF SATURATION
IN PERCENT
AS A % OF LONG TERM MEAN

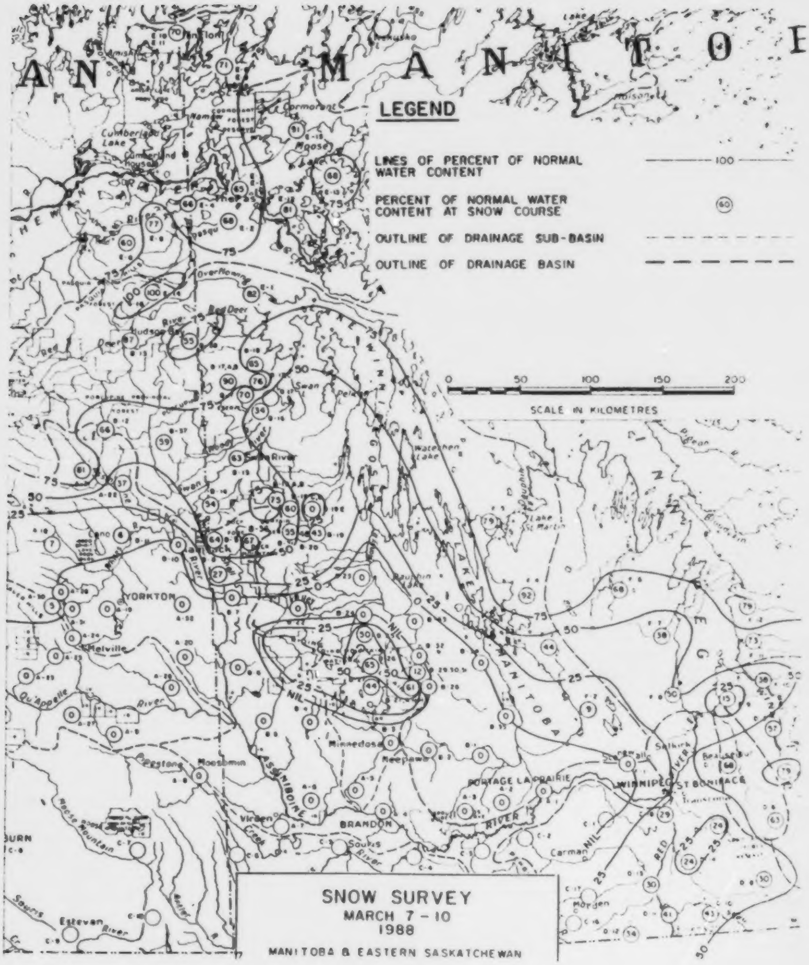
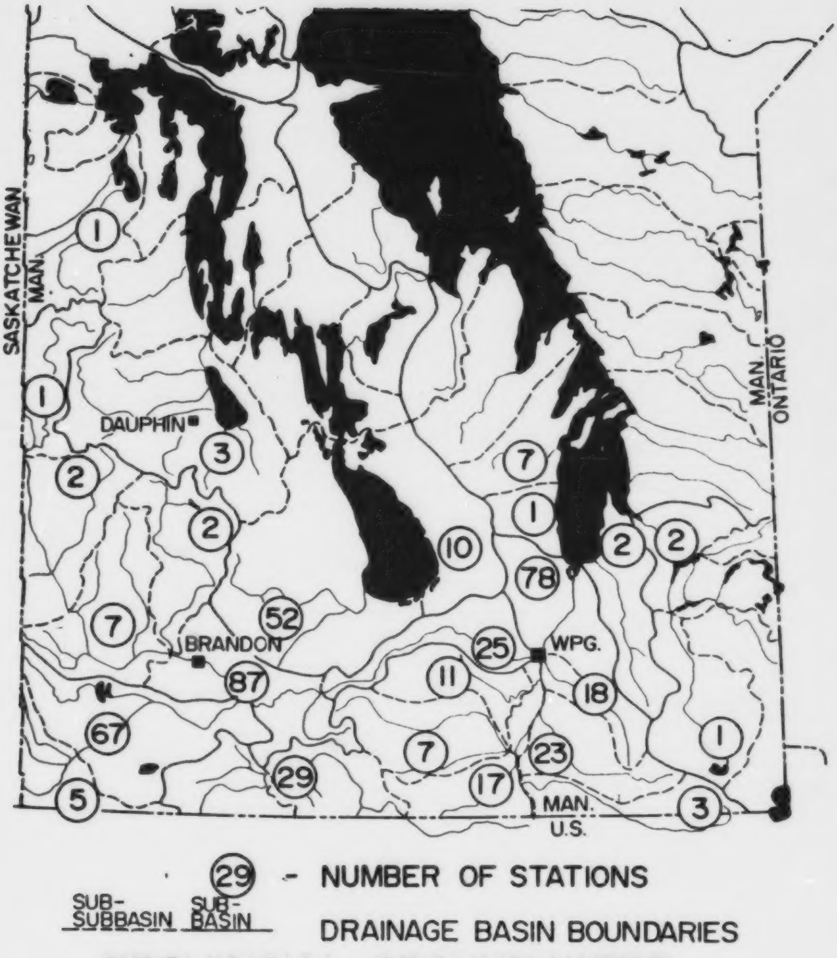
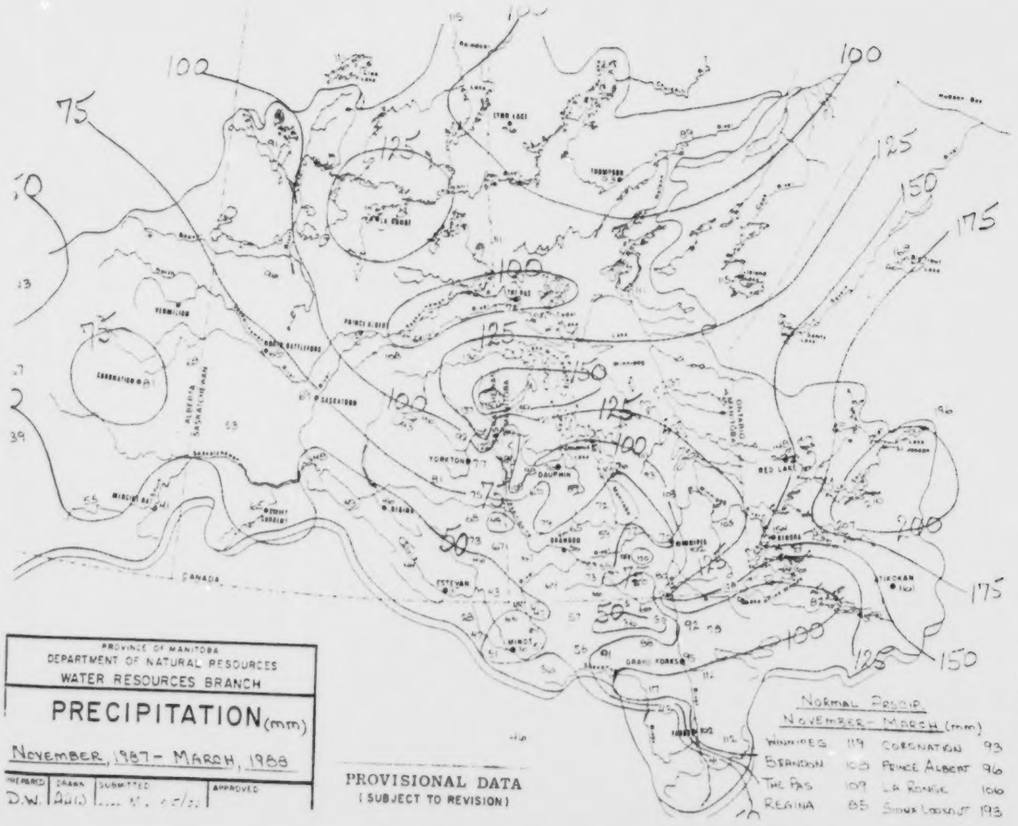

MANITOBA
LEGEND
LINES OF PERCENT OF NORMAL WATER CONTENT
100
PERCENT OF NORMAL WATER CONTENT AT SNOW COURSE
60
OUTLINE OF DRAINAGE SUB-BASIN
OUTLINE OF DRAINAGE BASIN
0 50 100 150 200
SCALE IN KILOMETRES
SNOW SURVEY
MARCH 7 - 10
1988
MANITOBA & EASTERN SASKATCHEWAN
YORKTON
Melville
Qu'Appelle River
Moosomin
Virden
BRANDON
Souris River
Minnedosa
Neepawa
PORTAGE LA PRAIRIE
WINNIPEG
ST BONIFACE
Selkirk
Carman
Morden
Estevan
Moose Mountain Creek
Cumberland Lake
Cumberland House
The Pas
Swan River
Dauphin Lake
LAKE MANITOBA
LAKE WINNIPEGOSIS
Waterhen Lake
Lake St Martin
ASSINIBOINE
RED RIVER

Figure 4


SASKATCHEWAN
MAN.
MAN.
ONTARIO
DAUPHIN
BRANDON
WPG.
MAN.
U.S.
1
1
2
3
2
7
52
87
67
5
29
7
17
23
11
25
10
7
1
78
2
2
18
1
3
29 - NUMBER OF STATIONS
SUB-SUBBASIN
SUB-BASIN
DRAINAGE BASIN BOUNDARIES

PROVINCIAL GROUNDWATER MONITORING NETWORK

Figure 5



100
75
50
125
100
125
150
175
100
125
150
125
100
75
50
200
175
150
125
100
75
Hudson Bay
Lynn Lake
Thompson
La Ronge
The Pas
Prince Albert
North Battleford
Vermilion
Coronation
Saskatoon
Alberta
Saskatchewan
Ontario
Manitoba
Yorkton
Dauphin
Brandon
Winnipeg
Red Lake
Estevan
Minot
Grand Forks
Canada

PROVINCE OF MANITOBA
DEPARTMENT OF NATURAL RESOURCES
WATER RESOURCES BRANCH

PRECIPITATION (mm)

NOVEMBER, 1987 - MARCH, 1988

PREPARED	DRAWN	SUBMITTED	APPROVED
D.W.	AW	....	

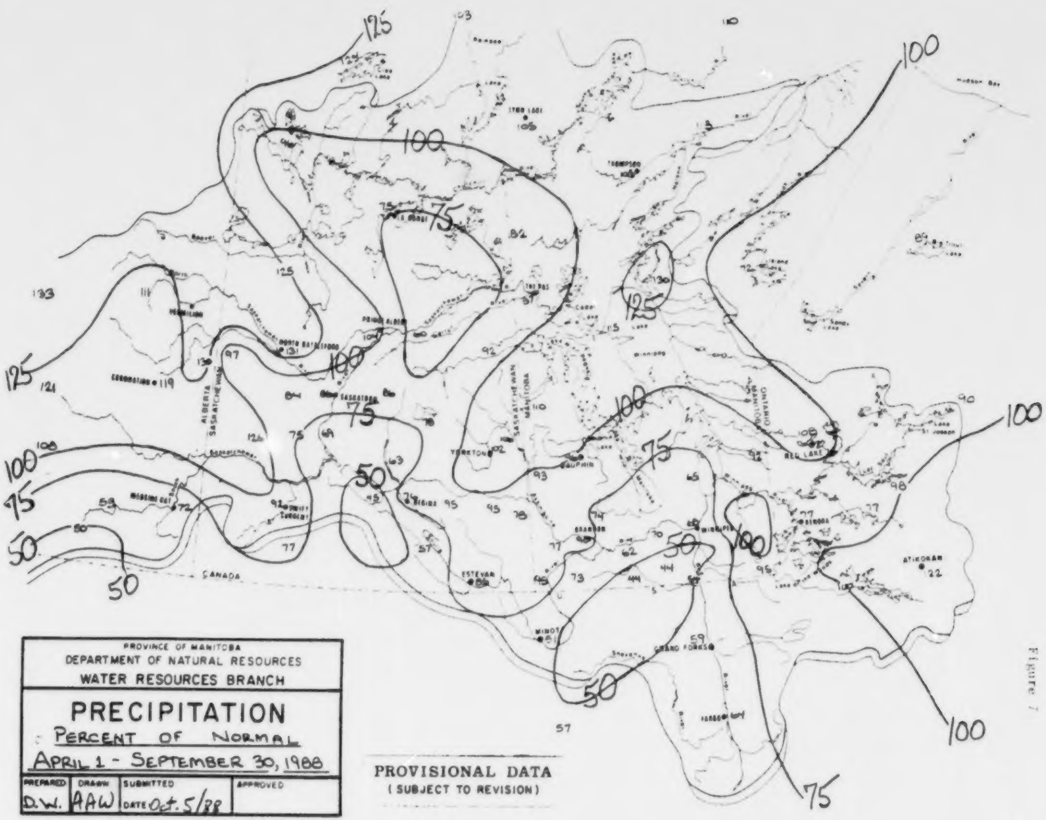
PROVISIONAL DATA
(SUBJECT TO REVISION)

NORMAL PRECIP
NOVEMBER - MARCH (mm)

WINNIPEG	119	CORONATION	93
BRANDON	103	PRINCE ALBERT	96
THE PAS	109	LA RONGE	100
REGINA	85	SIOUX LOOKOUT	193

Figure 6

Figure 7



125
100
75
50
125
100
75
50
100
100
75
CANADA
ALBERTA
SASKATCHEWAN
MANITOBA
ONTARIO
Hudson Bay
THOMPSON
PRINCE ALBERT
SASKATOON
YORKTON
DAUPHIN
BRANDON
WINNIPEG
ESTEVAN
MINOT
GRAND FORKS
RED LAKE
KENORA
ATIKOKAN
MEDICINE HAT
CORONATION
133
121
119
108
131
130
22
57
59

PROVINCE OF MANITOBA
DEPARTMENT OF NATURAL RESOURCES
WATER RESOURCES BRANCH

PRECIPITATION
PERCENT OF NORMAL
APRIL 1 - SEPTEMBER 30, 1988

PREPARED	DRAWN	SUBMITTED	APPROVED
D.W.	AAW	DATE Oct. 5/88	

PROVISIONAL DATA
(SUBJECT TO REVISION)

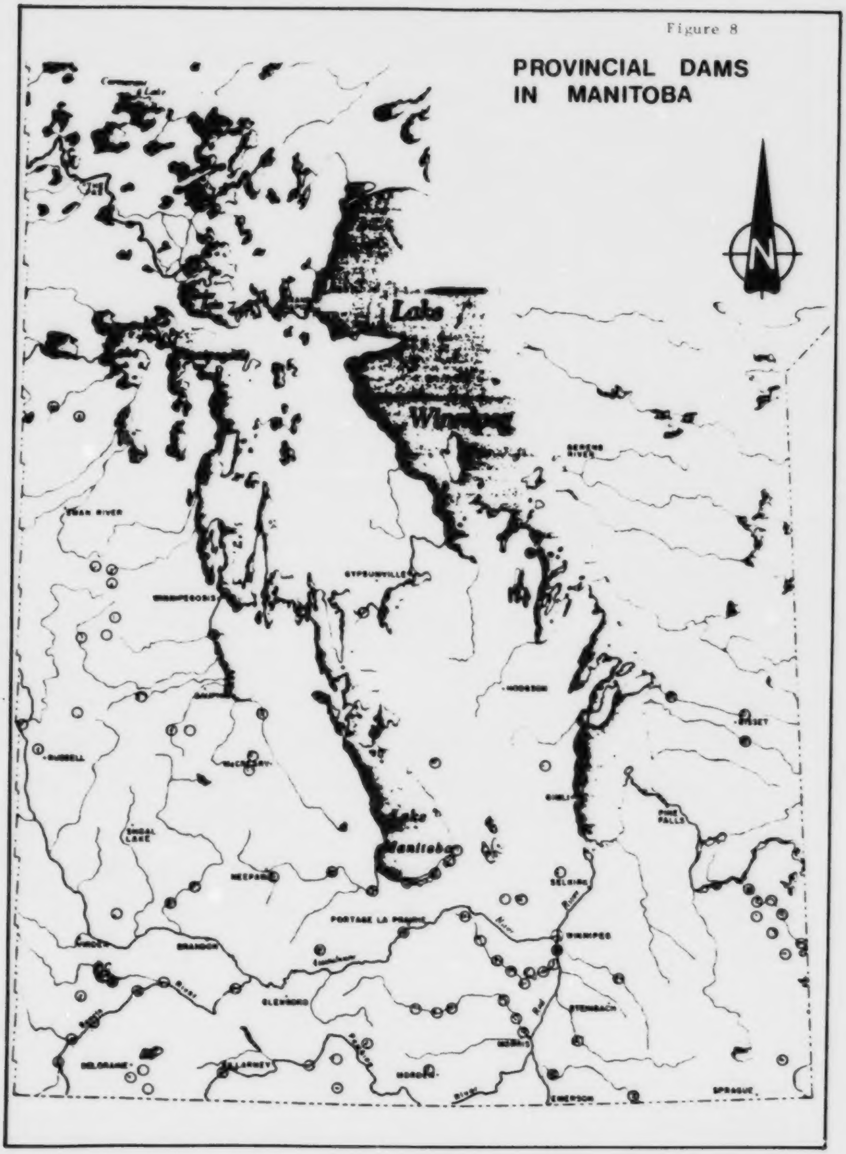


Figure 8

PROVINCIAL DAMS IN MANITOBA

Cormorant Lake
Lake Winnipeg
BERENS RIVER
SWAN RIVER
GYPSUMVILLE
WINNIPEGOSIS
HODGSON
BISSET
RUSSELL
McCREARY
GIMLI
PINE FALLS
SHOAL LAKE
Lake Manitoba
NEEPAWA
SELKIRK
PORTAGE LA PRAIRIE
VIRDEN
BRANDON
Assiniboine River
WINNIPEG
GLENBORO
Souris River
STEINBACH
MORRIS
DELORAINE
KILLARNEY
MORDEN
Red River
EMERSON
SPRAGUE

PROVINCE OF MANITOBA

UPDATED

DEPARTMENT OF NATURAL RESOURCES

WATER RESOURCES BRANCH

MAJOR LAKES IN SOUTHERN MANITOBA

Provisional Lake Levels for Month of September 1988

All elevations in metres above sea level

LAKE	CODE	LOCATION	YEARS OF RECORD	Long Term Means		Desireable Range of Levels	Last Year's Weekly Means					This Year's Weekly Means				
				Annual	Sept		to Sept 5	to Sept 12	to Sept 19	to Sept 26		to Sept 3	to Sept 10	to Sept 17	to Sept 24	
Brereton	3	Campground	24	315.87	315.83	315.7-316.2	315.86	315.85	315.82	315.81		315.89	315.87	315.86	315.89	
Dauphin	1	Outlet	36	260.43	260.38	260.0-260.4	260.23	260.19	260.17	260.21		260.29	260.28	260.24	260.23	
Falcon	3	Falcon Lake	13	324.70	324.65	324.52-324.82	324.80	324.77	324.76	324.74		324.75	324.72	324.70	324.70	
Killarney	3	Killarney	26	492.14	492.06	492.1-492.4	492.33	492.29	492.26	492.26		491.55	491.50	491.49	491.50	
Lake of the Woods	1	Hanson's Bay	72	322.82	322.94	321.85-323.50	322.56	322.57	322.57	322.60		322.52	322.63	322.71	322.83	
St. Martin	1,3	Hilbre	62	243.24	243.14	243.25-243.85	242.83	242.80	242.80	242.78		242.87	242.78	242.76	242.82	
Manitoba	1	Steep Rock	62	247.52	247.48	247.15-247.75	247.47	247.43	247.43	247.44		247.34	247.36	247.30	247.29	
Nutimik	3	Campground	27	274.82	274.76	274.50-274.95	274.11	274.15	274.20	274.18		274.15	274.10	274.15	274.22	
Oak	1,3	Oak Lk. Resort	22	429.51	429.46	429.15-429.80	429.57	429.53	429.50	429.46		428.96	428.87			
Pelican	3	Ninette	31	411.64	411.36	411.80-411.95	411.36	411.34	411.33	411.33		410.80	410.77	410.80		
Rock	3	Avery's Point	24	405.00	404.85	404.5-405.1	405.39	405.34	405.30	405.26		404.83	404.81	404.79	404.79	
West Hawk	3	Campground	22	332.45	332.43	332.5-332.7	332.50	332.48	332.46	332.45					332.32	
White	3	Campground	19	305.46	305.42	305.4-305.7	305.51	305.50	305.51	305.51		305.71	305.70	305.72		
Winnipeg	1	Gimli	70	217.44	217.53	216.70-217.95	217.57	217.65	217.57	217.57		217.01	216.91	216.98	217.13	
Winnipegosis	1,3	Winnipegosis	71	253.08	253.11	253.0-253.6	253.24	253.20	253.22	253.21		253.28	253.29	253.25	253.31	
Lake of the Prairies	1	Shellmouth	16	425.84	426.50	426.7-427.5	427.24	427.15	427.10	427.02		427.33	427.23	427.16	427.15	

Field data collected and provided by:
1) Canada Water Resources
2) Manitoba Hydro
3) Manitoba Water Resources

1 metre = 3.2808 feet

Figure 9

** Precipitation Data for Southern Manitoba

Figure 10

	Percent of Norm API	Winter Precip. (Nov.-Mar)	April	May	June	July
1972-73	91	64.9	32.0	53.5	100.7	80.2
1939-40	87	68.8	28.7	42.8	74.0	69.5
1980-81	132	72.4	13.6	53.7	101.0	61.7
1951-52	88	75.8	6.2	14.8	98.9	54.1
1976-77	54	78.5	6.7	99.0	88.9	112.2
1983-84	92	79.8	61.5	33.6	111.5	45.4
1957-58	105	80.7	19.5	14.8	51.7	98.6
1987-88	102	81.5	9.1	56.7	42.2	86.9
1953-54	112	83.3	49.9	53.5	139.5	47.7
1936-37	66	84.4	64.7	57.9	81.3	94.1
1981-82	135	84.6	20.6	52.3	50.5	122.4
1943-44	90	94.2	13.0	67.6	180.5	62.0
1962-63	119	94.6	59.3	62.2	120.2	77.4
1959-60	145	96.8	39.0	60.2	53.2	37.7
1979-80	73	99.2	0.8	11.7	59.3	58.9
1984-85	134	99.5	16.0	59.3	90.4	25.6
1950-51	109	99.7	30.7	17.1	57.2	34.8
1967-68	75	100.8	32.3	61.2	71.8	97.5
1932-33	89	100.8	23.2	86.3	28.7	28.5
1971-72	132	101.6	21.6	45.9	58.4	52.0
1964-65	91	101.8	45.1	96.2	54.4	92.3
1970-71	113	102.5	50.7	27.0	132.3	88.0
1969-70	101	103.3	68.3	66.1	67.0	100.3
1960-61	81	105.0	40.4	25.6	8.5	54.3
1952-53	70	105.4	22.5	95.0	122.1	98.9
1977-78	136	106.9	27.2	88.9	54.6	87.4
1985-86	136	110.6	72.4	57.6	65.6	114.7
1933-34	88	110.7	18.2	16.7	73.1	30.2
1945-46	102	112.2	15.3	28.3	60.5	85.1
1963-64	84	112.2	40.4	55.7	92.6	84.5
1935-36	114	113.8	12.9	32.4	71.9	28.0
1938-39	62	114.1	19.0	42.3	85.3	56.6
1949-50	113	114.8	33.3	92.7	95.5	93.5
1974-75	86	115.1	65.4	37.7	105.1	54.8
1982-83	137	115.7	6.4	39.8	95.7	63.2
1946-47	104	116.6	28.4	21.3	140.4	35.1
1954-55	128	120.1	34.2	60.0	96.6	63.8
1940-41	93	120.3	39.1	74.8	68.8	53.2
1941-42	137	122.6	38.9	54.6	54.3	97.9
1965-66	116	123.4	45.3	34.3	69.1	61.8
1966-67	80	123.8	76.5	18.7	42.4	56.5
1956-57	97	128.9	30.3	41.2	94.0	63.3
1947-48	99	129.0	54.6	38.9	64.1	117.9
1937-38	111	129.9	27.4	43.4	51.1	66.3
1934-35	74	132.5	26.8	41.3	142.7	103.4
1958-59	75	134.4	19.5	91.3	64.2	57.4
1986-87	95	135.5	6.1	42.6	61.6	106.0
1942-43	93	138.7	12.7	77.7	84.6	69.5
1961-62	63	139.0	15.3	128.0	54.2	91.0
1968-69	129	140.3	25.4	46.6	86.4	78.6
1948-49	71	141.2	6.0	73.3	60.7	83.7
1944-45	123	150.0	36.3	39.6	78.2	74.4
1978-79	108	153.2	58.7	78.9	48.8	53.3
1973-74	152	155.1	55.0	108.5	24.5	41.7
1975-76	132	156.8	30.8	12.0	135.2	26.7
1955-56	98	216.3	6.9	46.4	98.1	79.4
Median	100	111	30	53	72	67

** Data are means of values at (or near) Brandon, Dauphin, Gimli, Morden, Pierson, Portage, Russell, Sprague, and Winnipeg.

Figure 11

LAKE of the PRAIRIES

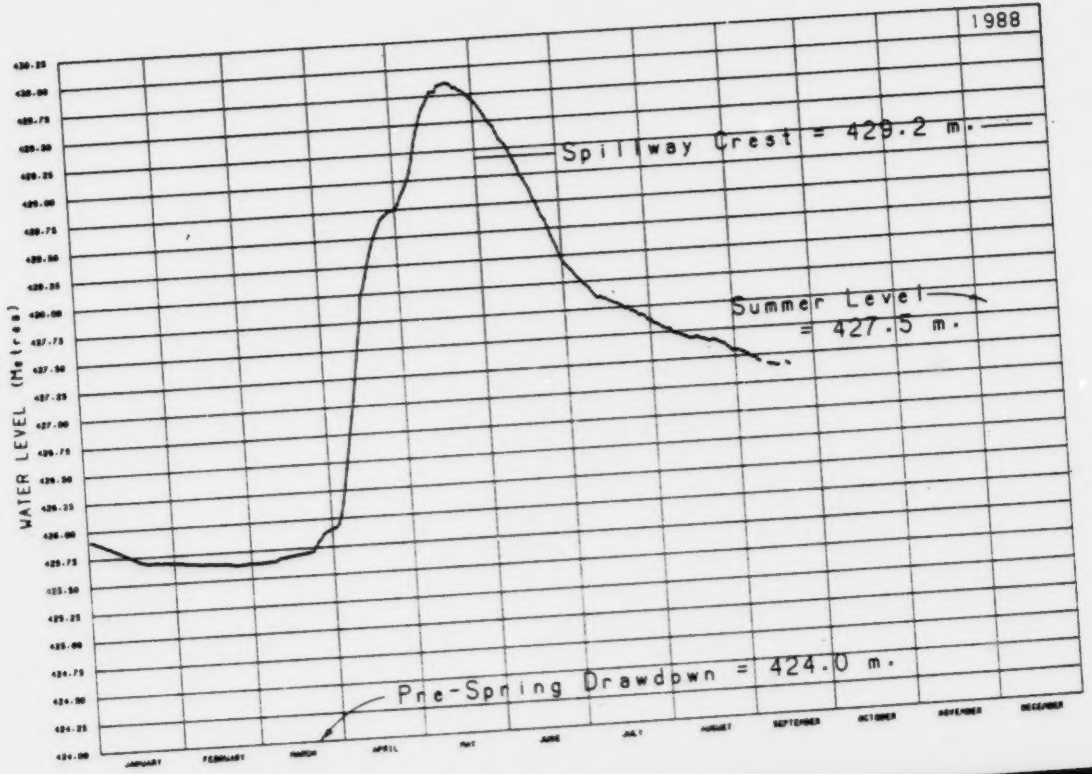


Figure 12

MORDEN RESERVOIR

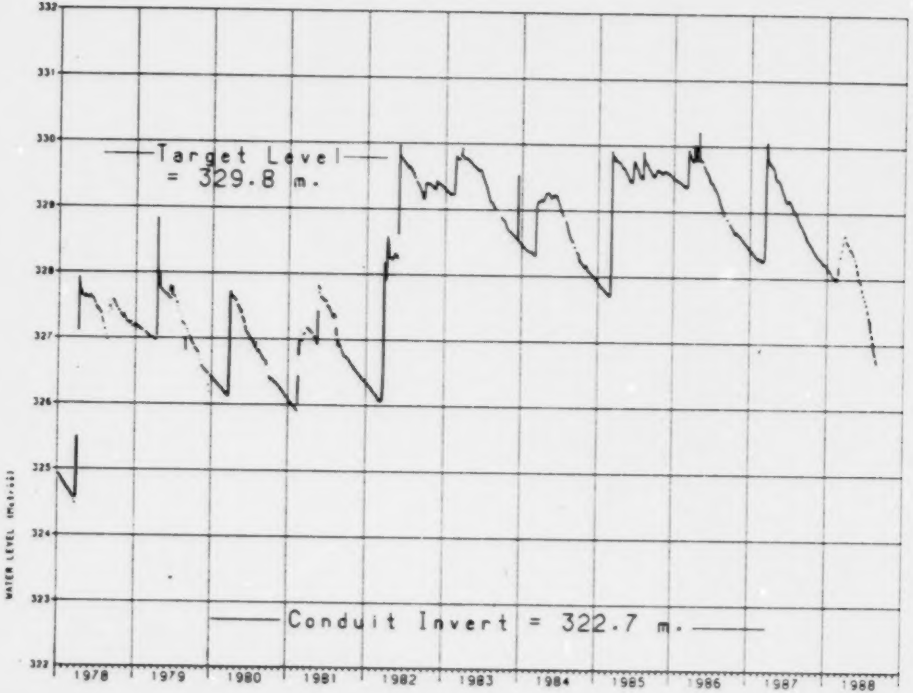


Figure 13

ECONOMIC IMPLICATIONS

1988 HYDROLOGIC DROUGHT IN MANITOBA

1. MANITOBA HYDRO DEFICIT OF $60 MILLION

2. FOREST FIRES, REFORESTATION - $8 MILLION

3. PFRA DROUGHT MITIGATION - APPROXIMATELY $3.5 MILLION

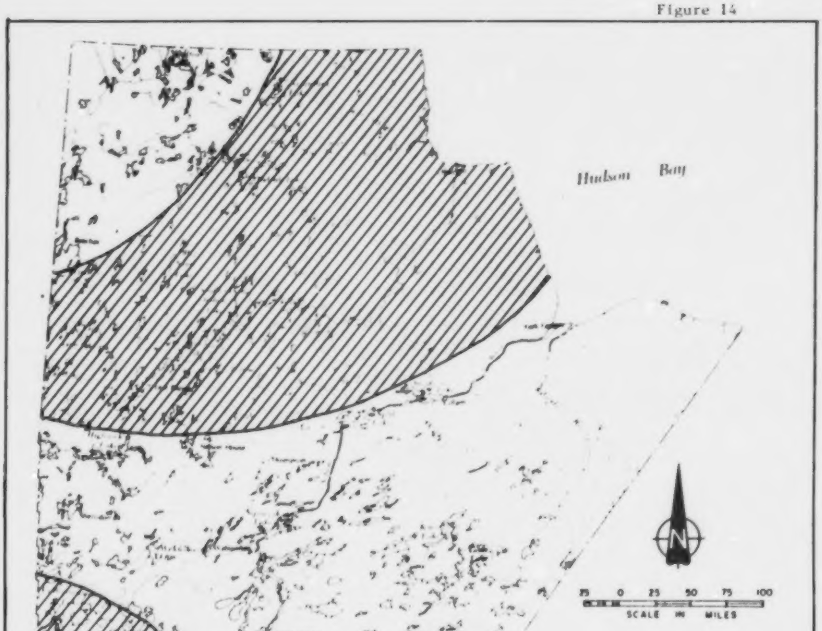
4. MANITOBA NATURAL RESOURCES COSTS (OTHER THAN FORESTRY) -- $2.8 MILLION

5. WATER SERVICES BOARD COSTS - $2.3 MILLION

6. LONG-TERM COSTS TO FISHERIES, WATERFOWL PROGRAMS

7. ECONOMIC HARDSHIPS TO INDIVIDUALS

Figure 14


Hudson Bay
Lake Winnipeg
25 0 25 50 75 100
SCALE IN MILES
N
LEGEND
SPRING RUNOFF POTENTIAL
BASED ON
MEDIAN WEATHER CONDITIONS
LESS THAN 25% OF NORMAL
25% TO 50% OF NORMAL
50% TO 75% OF NORMAL
75% TO 100% OF NORMAL
DEPARTMENT OF NATURAL RESOURCES
WATER RESOURCES BRANCH
SPRING RUNOFF OUTLOOK
FORECAST DATE: MARCH 16, 1988
PREPARED BY A.A.W.

FBR.-880316

B-4

Figure 15

EFFECT OF TEMPORAL DISTRIBUTION OF ANNUAL PRECIPITATION OF RUNOFF FOR STURGEON CREEK (576 KM^2)

	1977	1979	RATIO (79/77)
RUNOFF	6390 dam^3	83,100 dam^3	13:1
PRECIPITATION	650 mm	490 mm	0.75:1

	SEPT./76 -AUG./77	SEPT./78 -AUG./79
PRECIPITATION	485 mm	584 mm

	SEPT./76 -APR./77	SEPT./78 -APR./79
PRECIPITATION	83	314

Session 2 - Working Group Questions and Issues

General

Working Groups can choose to address two or three of the following questions and issues, or adapt them, or devise their own questions.

2.1 Drought Definitions and Indices

Drought is difficult to define except in the precise context of particular impacts. Given this, comment on the utility and appropriateness of current use of drought indices such as the Palmer Drought Index and the Crop Moisture Index.

Is it possible to have a single definition of drought, or an improved index (perhaps, for example, a "super" index based on physical/agricultural/econometric models, and expressing impact in dollars), which would be generally useful as an early indicator to all drought response agencies? How can the problem of providing accurate information on drought to the public and political system best be addressed, especially in the early stages of a developing drought?

Can a meteorological definition of drought combining temperature (i.e. potential evapotranspiration) and precipitation deficits be devised so as to be widely useful?

2.2 Network Design and Sufficiency

Are existing meteorological, hydrological and agricultural observing networks adequate to identify the onset, progress, severity and extent of drought in the Prairies, in order to meet the needs of the drought response agencies? If not, in what way need they be improved to become adequate, if that is feasible?

Is there a need for improved cross-border (U.S./Canada) communication of the near real time data currently gathered? How about improved near real time data archiving in Canada of water related data?

Many observing stations are being closed or will be radically changed through automation. Is there a compelling need for a reference network of long-term hydrological/meteorological stations for drought research? Can the nature of the need be specified so as to allow determination of criteria for such a reference network?

2.3 Statistical Characterization of Drought

How should the three main types of drought (hydrological, meteorological and agricultural drought) be best statistically represented? Should medians and percentiles replace normals and percentage of normals when reporting precipitation amounts or streamflow, for example?

What kinds of output is best from soil moisture modelling (e.g. mm of moisture, percent of field capacity, percent of normal, percentiles, etc.)?

What are the limitations of frequency analysis of drought events given the current instrument record?

Can paleoclimatic information provide sufficiently comparable drought data to the instrumented record to allow use of standard frequency analysis over the combined period of record? Or must such data always be analyzed separately except for subjective comparison?

2.4 Remote Sensing

What drought indicators or parameters will satellite-based remotely sensed data be able to provide in the 1990s? Will these data fill the serious geographic gaps in the ground based record. (for example, the mountain snow pack)? Or will such data tend to relate to specific impacts (example of the latter--impact on a specific crop type) and be difficult to relate to traditional measures of drought?

How and to what extent can the evolving technologies be best exploited, both scientifically and in terms of information transfer to drought response agencies?

2.5 Geographic Progression of Drought

Is there a pattern of severe drought progression which, in order to achieve the earliest possible detection, requires monitoring of the onset of drought in a detailed manner on a continental basis (rather than separately for Canada and the U.S.)?

Is there a need for improved cross-border (U.S./Canada) communication of the near real time data currently gathered? If so, which agencies should take the lead in this regard and what data is required?

2.6 Multi-Year Drought

Comment on the drought period of the 1980s versus that of the 1930s. Can one be definitively stated to be more severe than the other if societal/economic/technological factors were able to be held constant?

How can drought be defined to achieve a statistically stable and useful definition of multi-year drought in order to allow comparison of severe multi-year droughts? Here, statistically stable refers to the idea that the assessed severity should change marginally given small changes in the defining parameters (such as those used to determine drought duration, for example).

DROUGHT MONITORING, DETECTION & EARLY WARNING

Summary

W. Nicholaichuk - Session Chairman

Mr. Jim Laver of the Climate Analysis Center of the U.S. National Weather Service, a keynote speaker for the session, provided an excellent basis for the workshop discussions on drought definations and indicies, network design and sufficiency, remote sensing, geographical progression of drought and multi-year droughts. This summary reviews the highlights and itemizes the recommendations arising from the working group discussions.

Drought was found difficult to define except in the precise context of particular impacts. A 'holistic' index is ideal but is impractical. Although the P.D.I. and C.M.I. indicies are recognized as not being perfect, they are worth maintaining. The main problem with indicies are that they are useful on the supply side but do not exist for the demand side for water requirements. It is essential that the time scale be adopted to fit the particular drought in question.

Furthermore, indicies are being used for purposes other than what they were designed for. As a result, it is necessary to educate both the users of indicies and the public who respond to information based on these indicies.

Standardize network designs should be standardized to improve network quality. Since many networks are designed for specific objectives in mind, it may be necessary to supplement a 'standardized network' with radar and satellite imagery. Since data originates from a number of different sources, a data management plan is required. Cross-boundary differences (ie. U.S.A. and Canada) should be resolved in order to expand the usefulness of existing data networks.

The development of Geographical Information Systems coupled with satellite data and existing data networks should be encouraged. This system would be linked with existing groundwater monitoring networks to provide a comprehensive data base for monitoring droughts.

The existing networks for monitoring drought were considered adequate except for soil moisture. Hydrometerological networks do provide a means of detecting early warning signals of an impending drought based on fall soil moisture and snow pack accumulation and distribution. However, regional groundwater monitoring networks are considered inadequate for monitoring drought.

Remote sensing for drought detection, and monitoring has not been fully exploited. The main thrust of research should be in the area of remote sensing applications. There is a need to interpret the signals with respect to snow depth and water equivalent and soil moisture. This data should be supplemented with ground truth measurements. Since hydrometrological information appears to be the best indicator of pending droughts, the application of remote sensing technology combined with Geographical Information Systems should be a priority in drought research.

With respect to the geographical progression of drought, a general consensus emerged that there is a need for improved cross-border (U.S./Canada) communication for real time data. Suggestion was made that arangements be made that data be standardized for this purpose and be centralized within agencies in both U.S. and Canada.

Analysis of multi-year droughts indicatede the drought of the 1980's was more severe than that experienced in the 1930's. For example, in agriculture, the crops production and quality were more severely affected, cattle populations were decreased severely, and costs rose significantly. From a meterological standpoint, precipitation deficits were similar but temperatures were higher. Hydrologically, the natural flows were lower than the 1930's. For example, Old Wive's Lake is drier now than on the 1930's. From a wildlife perspective, duck populations are at a all time low which has a dramatic effect on the industry (40,000 jobs and a billion dollars).

Recommendations that followed from the group discussions are sumarized as follows:

1. Although the P.D.I. and C.M.I. are not perfect, they should be maintained. Time scales should be adopted that fit the drought in question.

2. It is necessary to educate both users of indicies and the public who respond to information.

3. A data managment plan should be developed that accomodates various data sources. In additon, there is a need to standardize network designs to improve data quality and a need to improve soil moisture monitoring.

4. Research in the area of remote sensing applications to monitor snow depth, water equivalent and soil moisture should be encouraged.

SESSION 3

DROUGHT PREDICTION

NON-FEASIBILITY OF LONG-RANGE FORECAST OF DROUGHTS

by

Vujica Yevjevich
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ABSTRACT

To increase the communication, definitions and distinctions of terms are first given. An analysis of various claims related to climatic changes are reviewed in light of what is definitely known to have occurred, what are the contemporaneous controversies and plausible conclusions on climatic variations and climatic changes of the immediate future. The position on climatic-hydrologic variations and changes are summarized.

The methods of forecast of drought-related variables and particularly the long-range forecast of droughts are analyzed in the light of what may be considered as the present state-of-the-art. The short-range, middle-range and long-range forecast feasibility by circulation models (either atmospheric only, or atmospheric-oceanic-continental models) should be measured by a proper forecast feasibility parameter, which is proposed in this paper. The long-range forecast by these models seems not yet to be feasible, though the short-range feasibility is currently accepted as good.

The time-lag dependence between the variables seems also not to have a large promise for the long-range forecast, because of high stochasticity of atmosphere. The example of coastal precipitation as related to the ocean temperatures may serve as the testing case.

The methods of long-range drought forecast by using the relationships between the climatic-hydrologic variables and the sunspot numbers seem to be overplayed. The use of any strict statistical method of testing does not show a significant relationship between these variables.

Methods of forecast by using shifting patterns of high and low atmospheric pressure or by using the analogy with the past do not seem to go beyond the middle-range forecast (say one to a couple of weeks). Neither do the methods of forecast based on time series decomposition and extrapolation, by using the Fourier series analysis, promise any significant outlook for long-range forecast. A very large number of examples have unquestionably shown in the past that these methods are not feasible.

There is a need for properly assessing the power of each method for the long-range forecast of droughts via the forecasts of drought-related climatic and hydrologic variables. Besides, a research need exists for the combinations of two or more long-range drought forecast methods, in order to attempt an improvement of drought forecast feasibility.

1. DEFINITIONS AND INTRODUCTORY STATEMENTS

1.1 Definitions and Distinctions

Distinctions are made in this paper between the following terms:

(1) Climate is defined here as the integrated effects of a set of atmospheric and hydrologic variables on the societal wellbeing, regardless that the temperature and temperature related variables have been most closely associated with the climate in the public perception.

(2) Hydrologic variables of importance to understanding of climatic processes are: precipitation, accumulated snow and ice, evaporation and runoff. These variables represent the integrated effects of large sets of meterological variables in measuring the climatic variations.

(3) Drought is defined in terms of its effects on biological processes, water supply, and related activities, because the interest is minimal in droughts when they do not affect humans, flora, or fauna on the earth's surface, directly or indirectly.

(4) Drought means a time-prolonged water deficit, either at specific points or over areas of continental and island surfaces. The water deficit at any particular time is defined as the difference between the available water for immediate uses (water supply) and the water needed (water demand) for uses by humans in any beneficial form.

(5) Quantitative drought definition is the difference between the water supply and the water demand variables, clearly specified in any particular drought related problem, meaning that the drought definition cannot be separated from the type of water demand and water use.

(6) Drought forecast is the feasibility of finding, by any method available, what the climatic and hydrologic conditions will be in the future. The differences between the forecast values and the ensuing observations of variables at forecast times are mainly the inevitable errors of measurement, computation and observations.

(7) Drought prediction is the determination of probabilities of future drought occurrences by using the past observed or proxy data and mathematical statistics, probability theory and stochastic processes applied to

climatic and hydrologic drought-defining variables and their time series.

(8) Long-range drought projection is the determination of drought variable parameters for future seasons and years, in advance, with the middle-range forecast defined as the time range of one week to two months, and the short-range forecast for the times of up to one week.

(9) Feasibility of forecast represents here a concept based on differences between the future observed values and the forecast values, in such a way that the variance of these differences becomes much smaller (say being one-fifth to one-fourth, or defined by any similar criterion) than the variance of values observed in the past of these forecast variables at given times.

(10) Methods of forecast are assumed to be any technique available, such as physical models, statistical interrelationship of variables, stochastic models, or any other scientific approach to forecast, predict or project occurrences of time processes.

(11) Distinctions are made here between the following concepts related to the time series of climatic and hydrologic drought-defining variables:

  (i) Time variation of variables at any point of the earth's surface is composed of deterministic variation of the time series parameters, such as periodicity (daily, monthly, and seasonal periodic variations) and almost-periodicity (results of long-range astronomic extraterrestrial variations affecting the amount and distribution of solar radiation over the earth), and the stochastic variation (noise) around the periodic and almost-periodic fluctuations of basic parameters (mean, variance, and any other statistical parameter that describes properties of climatic and hydrologic drought-defining time processes);

  (ii) Trends in time series parameters are the climatic or hydrologic changes that are induced by humans or by disruptions of nature on any time scale of detection, representing nonhomogeneity of the trend type in parameters of time series; and

  (iii) Random and systemic errors, superimposed on unknown true variable values of nature, as unavoidable errors in observing and processing data, the systematic errors on any time scale, as the inconsistency of the trend type in series parameters and the random errors representing an increase of the variance of the stochastic (noise) component in time series.

1.2 Introductory Remarks

Imprecise definitions of climate and drought are obstacles in proper communication among professionals as well as between professionals and the general public. The particularly imprecise definition is related to "climatic changes" as well as how the changes are detected, even when they can be quantitatively defined. Climatic changes are not identical to climatic variations. Climatic variations occur under the unchanged basic relationships of causal factors of climate and their descriptive variables. Climatic changes, as the well-defined changes in basic parameters, are important for both the long-range forecast, the prediction (in statistical-probability terms) and projection of drought characteristics.

Humans are traditionally interested in any type of forecast of future events, especially when the events are of a disaster type and may effect lives and well-being. The experience with forecasts in the past has created a general public attitude of an easy acceptance of doom forecast, with forgiveness based on short memory when the forecast events either do not come through or they come in substantially different forms and at completely different times. This general attitude has enabled a creation of pseudo-scientific approaches to climatic forecast, based on questionable scientific methods, with controversial results. The public glamour in forecasting the worst outcomes is a serious obstacle to a rigorous scientific analysis of the feasibility of long-range climatic forecast in general, and of the long-range drought forecast prediction and projection in particular.

If the methods presently available for long-range forecast are shown to be unfeasible, at least during the future couple of decades, then the following scientific approaches to droughts become attractive:

(1) Search for "negative scientific results", namely that the nature of earth-bound atmospheric, oceanic, and continental climate-related processes do not permit a long-range drought forecast;
(2) Undertaking of careful investigation of presently available and new methods for climatic long-range forecast, with identifications of those scientifically based factors that may permit the middle-range forecast; and
(3) Stress on scientific efforts for obtaining the reliable long-range drought prediction (in probability terms) and projection by using both the observational and proxy data, as well as any inferred effects of society on climatic changes.

The contention that "the relative stability of the climate generally exhibited in the late 1950's and most of the 1960's cannot be expected to continue through the 1970's and 1980's (Schneider, 1976), should be seriously questioned. First, the stress in this questioning should be on the words "relative stability", "generally exhibited", "most of", which are the unprecise terms, and without the rigorous scientific background and proof. The stochastic nature of climatic variations, on any time scale, requires a very well documented statement of any one of the above terms. These terms relate only to the chance variations with no significant probability for the changes to be induced by some deterministic processes of well defined, natural causal factors. The society induced changes represent a special subject, to be purposely excluded in this questioning of "relative stability" and the other terms as used in the quoted statement.

This text follows two lines of presentation:

(1) an analysis of the concepts and outlooks of "climatic changes" versus "climatic variations"; and
(2) the feasibility and the outlook of any method presently available, or a combination of these methods, for the long-range forecast of droughts.

2. CLIMATIC CHANGES AND CLIMATIC VARIATIONS

2.1 Claims of Climatic Changes

Contemporary literature contains theories and claims for ongoing climatic changes. Some of these theories forecast the coming of a new ice age with the present-day climate called interglacial. Others claim a warming trend is at hand. These theories are based on: release of heat from various sources of energy; release and increase of carbon dioxide through burning of fossil fuels with the greenhouse-effect heating the lower atmosphere; changes in the composition of the atmosphere by the release of particulates which affect atmospheric transparency for solar radiation and heat storage; and similar factors. One theory calls for partial melting of Antarctic ice and rising of ocean levels; in the opposite extreme, the forecast of cooling will cause additional ice accumulation and the subsequent lowering of ocean levels.

Studies on the effects of releases of heat, carbon dioxide, particulates, and other changes in atmospheric composition represent the necessary and sound research goals in the analysis of society's influence on the earth's environments. However, forecasts of the above extremes for ongoing climatic changes contradict each other.

In analyzing the effects of an increased release of carbon dioxide into the atmosphere, four factors should be also considered:

(1) the potential of oceans to absorb additional quantities of carbon dioxide;
(2) the continuous augmentation of total vegetation on the earth's surface in feeding the increased population and in fiber and wood production, regardless of present forest depletions;
(3) the eventual extraction of carbon from the air for

syntheses of hydrocarbons; and

(4) the need for some heating of the lower atmosphere to compensate for an expected, relatively small, cooling of the earth's northern hemisphere due to future changes in solar radiation distribution over the earth (the Milankovich phenomenon of long-range, almost-periodic fluctuations in solar energy distribution over the earth) [1,2,3].

The society's effects on atmospheric composition and its transparency for radiation and irradiation waves represent the attractive objectives for monitoring the ongoing and potential future climatic changes. These aspects of the problem of climatic changes are not controversial.

2.2 Climate and Future Problems

Society's most practical problems exhibit a need for inferences on immediate future climate, say for the next 100-200 years. Fluctuations of warm and cold years, wet and dry years, as well as variations within the year, need to be studied in order to infer the climate of the near future from the most reliable data of the recent past. Then the probability may be very large that the future 100-200 years of observations will show this inference to be correct, within limits of sampling variations. Similar climatic characteristics will likely occur in future samples of climatic random variables in the next 100-200 years as they occurred in the last 100-200 years, provided the society's effects and unforecastable disruptions in natures on the earth's environments are properly taken into account. Some recent studies of dendrochronology [4] extend instrumental data into the past for several additional centuries, but with larger errors in data (because of limitations in accuracy of methods and data used) than the instrumentally obtained data. For several past centuries these data do not support any significant climatic change (change in the basic parameters) beyond the stochastic climatic variation, when one takes into account the likely errors in data and methods used to derive these series.

2.3 Long-Range Climatic Changes

It is generally accepted by most geophysicists that climatic changes occur in the long run. Long-range changes seem to occur as a result of astronomical factors related to changes in distribution of incoming solar energy over the earth's surface. Changes on an even longer time scale result from geotectonic processes such as the wandering of continental plates and orographic changes on continents.

The Milankovich [1] theory of astronomical causal factors of changes in solar energy distribution over the earth's surface shows regular, almost-periodic variations in the eccentricity of the earth's orbit (one complete oscillation in about 93,000 years), tilt or obliquity of the ecliptic (one complete oscillation in about 41,000 years), and precession of the equinoxes (about 21,000 years per one complete oscillation). These deterministic, almost-periodic astronomical movements produce long-range changes in parameters of climatic variables because of changes in the distribution of incoming solar energy over the earth's surface and over the seasons. These changes affect temperature, rainfall, snowfall, as well as sea levels because of changes in ice and snow accumulation on continents. They also determine general patterns of atmospheric and oceanic circulations. Furthermore, the question whether the solar radiation "constant" is really a constant is still an open scientific inquiry.

Historic evidence, particularly from the last Pleistocene ice age [5,6,7], confirms long-range changes in basic parameters of climatic random variables on the earth, as inferred from sea-core and ice-core chronological data of paleotemperatures. These changes undoubtedly affect the long-range processes of annual series of temperature, precipitation, evaporation, and water runoff at given locations as well as their fluctuations within the year. The main question needing an answer is: what are the rates of change in parameters over time, associated with these processes at different historic times and at various locations?

It can be shown from the best available instrumentally obtained data that present rates of change in parameters are so small for a time span of 100-200 years that annual processes of temperature, precipitation, evaporation and runoff maybe safely inferred to be *temporarily stationary* stochastic processes with corresponding periodic-stochastic variations within the year. The most reliable observational data on annual temperature, precipitation and runoff from the last 100-200 years show no significant change in basic parameters. This is particularly true when unavoidable nonhomogeneities (the human effects and various disruptions in nature), inconsistencies (systematic errors in data), and sampling fluctuations of process characteristics associated with finite realizations of any geophysical stochastic time process are properly taken into account. Especially significant for studying these changes are the annual processes of precipitation and river basin runoff [8], because they integrate effects of various climatic variables and processes.

Questions which highlight basic contemporary controversy among climatologists, hydrologists and other specialists in geophysics can be summarized as follows:

(1) Could natural climatic processes represented by their annual series be inferred as *temporarily stationary* (or *quasistationary*) with a very slow rate of change in basic parameters of these stochastic processes over a time period of 150-200 years in the recent past; and by

extrapolating this recent past could these processes be inferred as such for a period of 150-200 years in the near future?

(2) If this *temporary stationarity* is rejected, could it be expected that climate may evolve rapidly and that extreme events from some very distant past, especially the initial period of the present postglacial era, may suddenly occur now with the same probabilities of occurrence as in the distant past? This latter alternative does not seem very plausible considering the following argument and example.

The Biblical Noah inundation may well have been an event produced in the Middle East by a combination of extreme, long precipitation (40 days by Biblical records), prolonged warm weather and simultaneous melting and retreating of mountain ice, glaciers and/or snow. It is reasonable to expect an extreme precipitation event of the Noah type to occur by chance from time to time somewhere in the world (such as the 40-day precipitation event in Tunisia in September 1969, or similar examples). However, the other basic condition of rapid melting of large quantities of accumulated snow and ice does not exist at present at most continental areas of interest.

2.4 Present Controversies on Climatic Changes

Present controversies on climatic changes have important, practical implications for planning development, conservation and control of natural resources related to climate. Is it then legitimate (with a high probability that it is) to draw information from the characteristics of processes and available resources related to temperature, precipitation and runoff as observed in the last 150-200 years and to expect that similar characteristics will occur in the next 150-200 years? If this approach is not justified, is it feasible from a practical, reliable viewpoint for planners of climate-related natural resource developments to use various, mostly speculative, climate change theories? Could the characteristics in form of parameters of these processes suddenly or relatively rapidly evolve? In one extreme should it be implied that the climate could soon deteriorate into the start of a new ice age in northern parts of America, Europe, Asia and on large mountain chains of the world? Or, in the opposite extreme, should it be implied that unusually rapid heating could result in the partial melting of Antarctic ice and the subsequent rising of the oceans? Experience from the last 100-200 years does not support these latter hypotheses.

The build-up of ice sheets and large mountain glaciers is a relatively slow process while their melting may be relatively rapid [9]. This implies that the rate of change in the initial build-up of ice sheets and large glaciers is much slower than the rate of change during their depletion or disappearance. Therefore, a relatively rapid rate of melting of the last Pleistocene ice sheet in northern America and northern Europe, and of the glaciers on most of the world's large mountain chains cannot be interpreted to be the potential rate of build-up of a new ice sheet. Simply, the annual accretion of snow minus its melting cannot produce a rapid build-up of snow, ice sheets and glaciers. Besides, the extrapolation of the Milankovich astronomical, almost-periodic, long-range fluctuations in distribution of solar energy over the earth's surface as predictable, deterministic, astronomical processes [1,2], shows that for the next 100,000 years little build-up of an ice sheet in the northern hemisphere can be expected, though some minor cooling should be expected to take place [2,10].

2.5 Plausible Conclusions on Climate of Immediate Future

For a time interval of 350 years, say from the years 1800 through 2150 (175 years in the immediate past and 175 years in the immediate future), the following basic conclusions may be drarawn from investigations of annual time processes of precipitation and river basin water runoff, with a high probability that these conclusions would be confirmed by future observations.

(1) Processes of annual temperature, precipitation, evaporation, water runoff from river basins, and similar and/or interconnected processes may be considered as *temporary stationary* stochastic time processes at present, provided systematic errors in observed data (inconsistency), human effect on climate and hydrology as well as disruptions in nature (nonhomogeneity in data), and expected sampling fluctuations to be realized in these random processes, are properly taken into account.

(2) The major time dependence in annual climatologic and hydrologic series is produced by the complex processes of heat storage in the earth's environments and water storage in atmosphere and especially in river basins, with random fluctuations from year to year during these 350-400 years and periodic-stochastic fluctuations within the years. When processes on a time scale of several decades or a couple of centuries are discussed in comparison with results of analysis of actual geophysical processes which create the time dependence, any significant long-range dependence still has to be unmistakenly documented with a sound base of reliable data and appropriate mathematical statistical methods.

(3) The more ancient the data of observed (measured) or inferred variables (proxy data), the more likely it is that they contain significant systematic errors (inconsistency) and a large variance of random errors. The use of earlier less reliable instruments and measuring techniques, and the ensuing changes in instrumentation and techniques of measurements, as well as some envir-

onmental impacts on observational stations (such as growth of cities or trees around gages), support the existence of inconsistency and random errors in most time series even in instrumentally obtained data.

(4) The longer a series, the greater is the probability that some nonhomogeneity has been introduced into the data, produced either by society's activities or by some disruption (landslides, forest fires, volcano activities and similar events). The more remote the past data, the more likely these nonhomogeneities would have occurred (one would expect more accurate proxy data on ice layer or sea-core sediment from more recent depositions).

(5) The probability for the two means of the two subseries of an observed climatic time series to be nearly identical is very small. Sampling fluctuations which leave visual impressions of trends, jumps and slight cyclicity are often erroneously treated as population trends, jumps and regular cycles. Their interpretations may be a fundamental difference among scientists on how fluctuations are approached, tested and interpreted.

(6) Some approaches in describing time dependence in climatic and hydrologic annual series may often be the result, partly or fully, of inconsistencies, nonhomogeneities and sampling fluctuations, rather than the result of true properties of underlying geophysical processes as derived from very large sets of series from reliable station data all around the world.

(7) Claims for a significant relationship between climatic processes in the lower atmosphere and sunspots can be disputed either on the basis that the methods and statistical techniques used in developing the relationship are erroneous and without a proper test of their significance, or that the relationship is so weak that it is of small practical significance, or both.

(8) The analysis of only a limited number of stations, particularly when their sample series contain inconsistency, nonhomogeneity and evident sampling fluctuations in comparison with adjacent stations may well support a particular concept or explanation. But the analysis and conclusions cannot be justified by existing geophysical and/or historical evidences, because the reliability of available data from those stations may be in question.

2.6 General Interpretations

It is a common practice among researchers to abandon investigations, or not report results of investigations, if the research data do not support either the approach taken or hypotheses advanced. Mostly, confirming results are reported in the literature. A reasonable question may be posed, namely: Are, in some cases, the confirming results nothing more than the extremes of a sampling distributions for random variables with small probabilities for them to occur again at the same gauging stations. The well-publicized Bruekner 35-year climatic cycle, developed for the first 70 years of climatic and hydrologic data in Europe, was not supported by data from the next 40-50 years. If Bruekner had used a wider range of variables from several large regions of the world, it is likely that he would not have concluded that a regular 35-year cycle existed in the climatic and hydrologic processes as he did by using the European data only.

The study of most reliable data from climatological series leads to the conclusion that there is an unusually high stability of properties of major processes, particularly the stability in fluctuations of wet and dry years of precipitation. The proof of this approximate stability of various stochastic phenomena and the projection that this stability will likely continue for some time to come (say for a couple of centuries in the near future, provided the artificial influences are taken into account), are conclusions that are not as glamorous as the projection of a forthcoming ice age or of a future heating-up of earth's environments.

The above conclusion of temporary stability may give some comfort to those in practical fields of endeavor who plan artificial systems using natural resources and who make decisions based on the best data from the past by assuming that the near future will be very similar to the near past. Those who doubt this approach are invited to place themselves in the year 1890 (with some reliable, instrumentally obtained data of about 85 years long, available at that time) and to project the behavior of those observed phenomena for the period 1890-1975. How surprised they would be at the accuracy of their projections, based on the temporary stationarity of annual series of temperature, precipitation and runoff!

In conclusion, it can be a good approach, in studying the feasibility of long-range forecast of droughts, to keep in view these hypotheses:

(1) For the natural climatic and hydrologic processes, the forecast will be governed by the variations of drought-defining variables;

(2) The well-proven effects of society's activities, whenever based on hard evidence and reliable scientific methods, as the future climatic changes of the trend type, should be incorporated into any feasible long-range forecasts of droughts; and

(3) Even if some changes are proven to exist in variables, such as the temperature, the changes in basic drought-defining variables, such as precipitation, evaporation, evapotranspiration, runoff, water storage, etc., may be smaller than in temperature (even of an order of magnitude smaller), so that relatively modest changes in

temperature parameters may be partially de-emphasized for the long-range forecast of droughts.

3. STATE-OF-ART OF LONG-RANGE DROUGHT FORECAST

Methods available and state-of-art of long-range drought forecast are briefly reviewed here. No proofs, details or citations of a large number of reference are included.

3.1 Methods of Forecast by Circulation Models

The short-range forecast and attempts for the middle-range forecast of weather resources variables are presently based on two types of mathematical models: physical models of atmospheric circulation, and physical models of coupled atmospheric-oceanic (continental) circulation.

Forecasts by physical models of atmospheric circulation result by the solutions of differential equations that represent mathematical abstractions of laws of fluid mechanics and thermodynamics of atmosphere. They are mainly the techniques of short-range forecast of weather variables. The forecast time lag is defined here as the difference between the time of issuing the forecast of variable values and the time of their observations. The forecast time lag depends on the time span for which solutions of model differential equations become independent, or nearly independent, of the initial conditions (state variables) of these equations. The general experience of weather forecast seems to clearly point out that this dependence decreased rapidly as the forecast time lag increases. The practical time lag limits of forecast by physical models depend on the selected criterion when the forecast is considered no longer either sufficiently accurate or socially beneficial. For time lags that are greater than the time lag of the selected criterion, the forecast is then considered as not being feasible.

The time series of major weather variables have a relatively short memory as well as the short lags of significant cross correlation between these series. These memories result from limited time and space storages of heat, kinetic energy and water in the atmosphere. The short-memory of atmospheric time series (periodicity excluded) has led to approaches of incorporating the oceanic and continental processes, interactive with atmospheric processes, into the physical models. Because water is a much more conservative fluid than the air, as it concerns the storage of heat and kinetic energy, it creates a larger and longer memory in comparison with the memory in the series of atmospheric processes. It is logical to expect that dependence between forecast values by solutions of circulation differential equations and the initial conditions of these atmospheric-oceanic -continental model equations would be somewhat stronger and longer for the same time lags of forecast than the case is with the physical models of the atmospheric circulation only.

The expectations from the use of physical models of atmospheric-oceanic-continental circulations for a substantial increase in the accuracy of forecast values, seem to have been much greater than experience in forecast, though the short-range and middle-range forecasts have been improved.

The geophysical time processes at ocean and continents, as additional inputs for the atmospheric-oceanic-continental models, have long memories either in storage of energy (oceans) or in storage of both energy and water (continents). The energy and water interactions between the atmosphere on one side, and oceans and continents on the other side, are highly influenced by a relatively large stochasticity of nearly all the atmospheric space-time processes. This stochasticity-bound limitation makes less feasible the translation of these memories into a significant increase in forecast accuracy and forecast time lag, especially for purposes of long-range drought forecast.

The representation given in Figure 1 is an approximate schematization of forecasts resulting from the physical models of circulation in any form. Since for time $\tau = 0$, the forecast variables are already known in the form of observations, the forecast is perfect for this lag. The variance of differences between the forecast and observed values at the forecast time lags generally increase with an increase in the time lag. The forecast feasibility can then be measured by the expression:

$$F_f = 1 - \frac{\text{var}(x_\tau - x_{f,\tau})}{\text{var } x_\tau} \tag{1}$$

in which F_f = the forecast feasibility (deterministic forecast, x_τ = the observed values at the forecast time lags τ and $x_{f,\tau}$ = the forecast variables values. Then

$$S_f = 1 - F_f \tag{2}$$

may be considered as the non-feasibility of forecast. Since $\text{var}(x - x_{f,\tau})$ can increase as much as desired (say one can use random numbers for $x_{f,\tau}$, with any variance, as a demonstration of a bad forecast), the term $F_{f,\tau}$ of Eq. (1) has the maximum at $F_{f,\tau} = 1$ for the case of perfect forecast (with always $x_{f,\tau} = x_\tau$). The forecast with $F_f < 0$ means that it is inferior to the simple probability statement prediction. Thus, F_f does not possess the lower limit of zero.

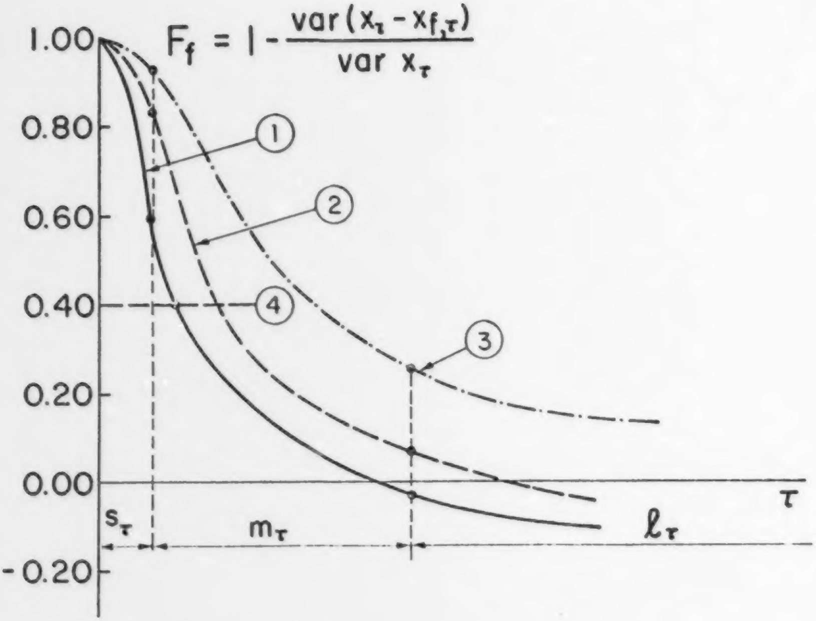


Figure 1. Generalized measure of feasibility of short-range (up to a week), middle-range (one week to two months), and long-range (longer than two months) forecast of drought-related weather, climatic and hydrologic random variables: (1) Standard forecast; (2) Expected improved forecast; (3) Season forecast based on accumulated water or snow in river basins; (4) Criterion of good (or acceptable) forecast feasibility; τ = the forecast time lag, s_τ = the short-range forecast; m_τ = the middle-range forecast and ℓ_τ = the long range forecast; and F_f = the forecast feasibility.

3.2 Methods of Forecast by Using Time-Leg Dependence Between Variables

Because the ocean stores energy better and longer than the atmosphere, a positive correlation should exist between the average temperature of the air above an area of ocean, for a given time interval, and the stored energy in surface ocean layers beneath the air. Similarly, the precipitation over a coastal area, or an island, should be physically related to the stored energy of nearby ocean surface layers. The reasoning behind these statements is that the larger the energy stored, the greater should be the average air temperature, ocean evaporation, and consequently the precipitation in the vicinity of ocean surfaces for all the other atmospheric factors being the same. Though these physical relationships are a correct approach for the study of the time lag dependence between the predictive (dependent) variables and the explanatory (independent) variables in any type of relationship the very important property of large stochasticity and high mobility of air masses in various directions, disrupt significantly these potential physical interrelationships. In other terms, the realistic relations are conditioned by a high stochastic variability of the atmosphere.

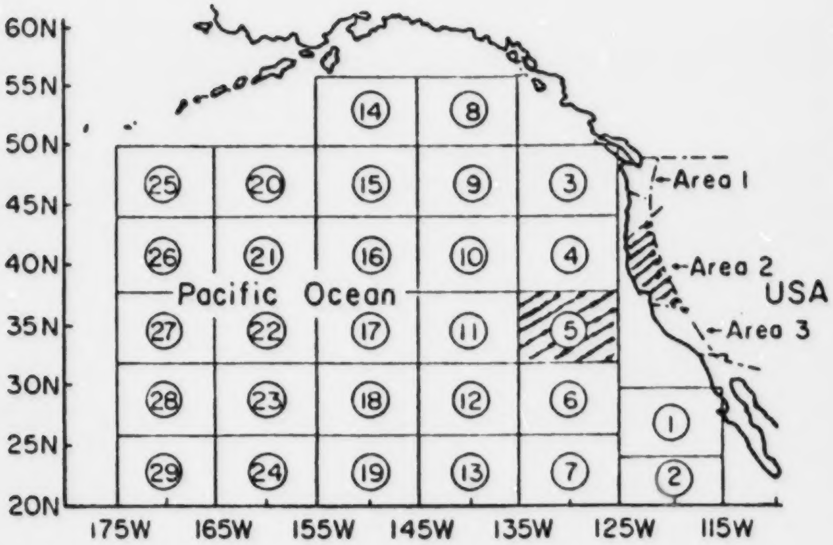
The attempts to relate the monthly precipitation of an area of the Pacific coastal region of the United States to monthly temperatures of specified areas of the Pacific Ocean around the coast have shown a positive correlation for the time lags of the order of 1-3 months. The major question that arose for this relationship was the significance of the computed multiple correlation coefficients for various time lags, conceived as the potential forecast lags.

Using the ocean surface temperature as an index of heat stored in the surface layers in delineated areas around a coastal area or an island, the total average monthly precipitation over the coastal areas or an island may show a positive relationship to these ocean temperatures. Whatever the multiple correlation coefficient found, the reliable statistical test should be performed to find whether it is significantly greater than zero. If one uses "n" areas of the ocean, each area with its surface temperature or the other heat storage measuring variables, the step-wise selection of the explanatory (independent) variables, such as temperature of the various areas, in the multiple regression and correlation approach, will have the analysis single out "m" significant explanatory (independent) variables. A correct testing method should then produce the upper tolerance limit to the zero multiple correlation coefficient of these explanatory variables assumed of not being related to forecast variables (say, monthly precipitation). This upper tolerance limit for a given probability level must be found for the condition of "m" explanatory (independent) variables selected by the step-wise method out of a total of "n" explanatory variables considered.

The procedures currently used in the application of step-wise multiple regression and correlation do not yet have the analytically developed distributions of the multiple correlation coefficient, with the parameters of the distribution expressed as a function of the number "m" of selected variables out of the "n" variables considered. It can be shown, by the use of generated samples obtained by the Monte Carlo method, under the realistic properties of series, that the multiple correlation coefficients, often even 0.30 - 0.50 do not come out to be very significantly different from zero. The larger "n" and the smaller "m", the greater the upper tolerance limit becomes. This fact requires the use of a proper testing procedure. Even when the multiple correlation coefficient of any lag comes out to be on the order of 0.10 - 0.20, these dependences between the forecast variables and the explanatory variables mean that only 1.0 - 4.0 percent of the monthly precipitation outcomes over a coastal area or an island, in the forecast intervals, are accounted for by the surface ocean temperatures, or by the stored heat in the neighboring oceanic areas. The 1.0 - 4.0 percents of outcomes, as feasible basis for the forecast, may not mean very much, when 96.0 - 99.0 percent of the outcome is governed by the chance that results from major properties of the stochastic processes of the atmosphere.

To illustrate the difficulties of relating the coastal monthly area precipitation to the nearby ocean area temperatures, for the western U.S. coast as shown in Figure 2, the monthly series of precipitation and temperature are first standardized as $\epsilon_i = (x_i - x_\tau)/s_\tau$, where x_i = the monthly values, x_τ = the monthly means and s_τ = the monthly standard deviations. The correlograms of the standardized monthly temperature series for the ocean area No. 5 (for area 5 see Figure 2) and of the standardized monthly precipitation series for the coastal area No. 2 (for area 2 see Figure 2) are given as Figures 3 and 4. While the first correlogram (for ocean temperature) has a long memory, the second correlogram (coastal precipitation) shows to be nearly an independent time series. This simple comparison of correlograms shows that the correlative relationship cannot be very high, as well as that the stochasticity of the atmosphere significantly disrupts the effects of the memory inherent in the stored heat of ocean surface layers. However, errors in estimating the mean monthly ocean surface temperatures (as indices of the heat stored) and the differences inherent in using the ocean temperature as an index of stored heat, limit significantly the power of forecast by the multiple regression and correlation approach.

In general, it is expected that the future may eventually show the forecast of climatic and hydrologic variables to be somewhat feasible for time lags of a couple of months, physically justified and statistically tested by using several atmospheric, oceanic and continental variables that precede the occurrence of forecast variables. If physically justifiable time lags of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35N
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25N
20N
175W
165W
155W
145W
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125W
115W
Pacific Ocean
USA
Area 1
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Area 3
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Figure 2. Areas (1,2,3) of monthly coastal precipitation and areas (1-29) of monthly ocean surface temperatures, for studying the correlation between these variables.

dependence are proved to be sufficiently long or sufficiently high by using the reliable testing methods, the forecast of climatic and hydrologic variables related to droughts may be feasible for a couple of months in advance. This type of analysis and forecast will require a large quantity of reliable data, and the most powerful tests to find how significant are the underlying dependence and time lags of forecast.

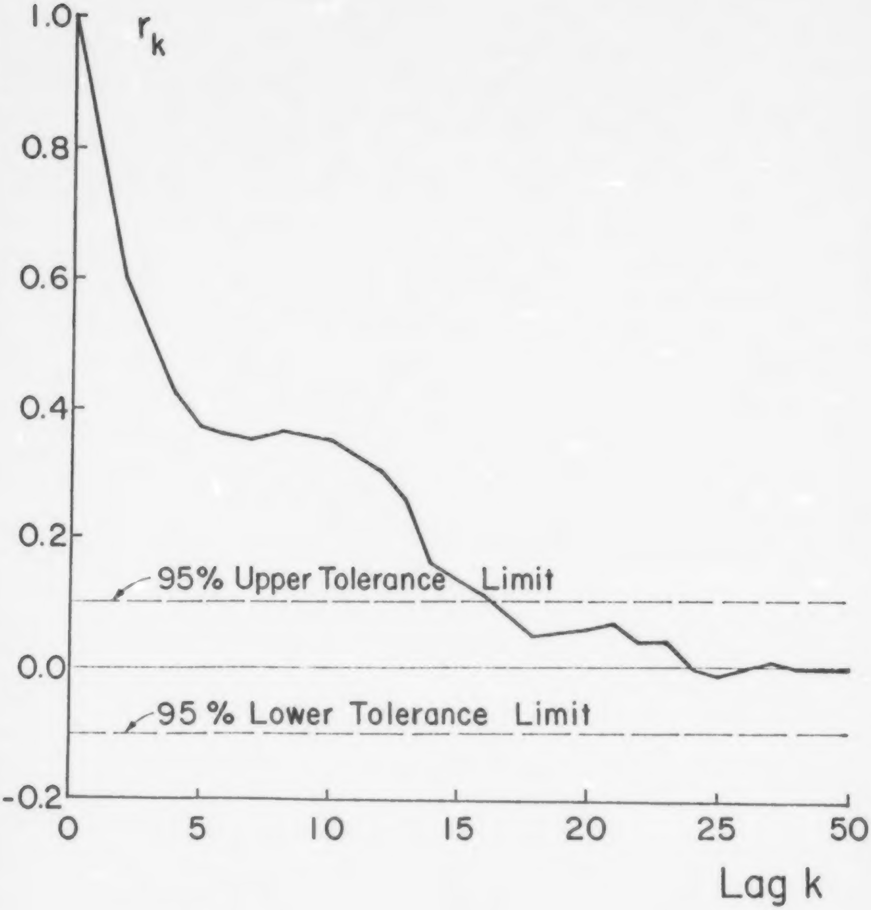

Figure 3. The correlogram of the standardized series of average monthly temperature of ocean surface No. 5 (See Figure 2) showing a long memory (dependence) of up to 24 months.

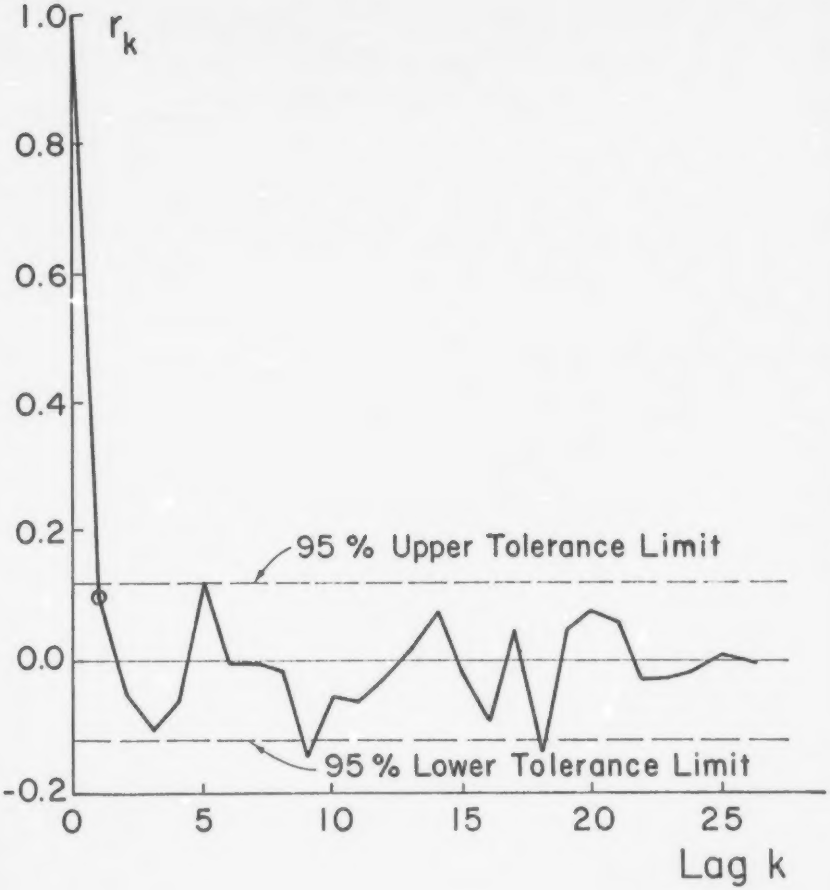

Figure 4. The correlogram of the standardized series of the average monthly precipitation of the U.S. coastal area No. 2 (See Figure 2), showing very small series dependence, even for the lag one.

3.3 Methods of Forecast Based on Relationship of Terrestrial and Extraterrestrial Variables

The relationships of climatic and hydrologic variables, including drought variables, to sunspots have been in focus and professional interest for some time. Even at present, the claims are often made that droughts of the Great Plains in the United States occur approximately at intervals of 22 years, the double cycle of the maxima or minima of sunspots. Three aspects of this interrelationship are important:

(1) How the sunspots physically affect the weather phenomena on the earth in general, and droughts in particular,
(2) What is the significance of their effects, and
(3) Do rigorous and correct statistical analyses and tests support a significant relationship between drought variables and sunspots for various time lags of forecast?

Another question seems logical, namely whether mathematical statistical techniques used in producing the conclusions on relationships between climatic variables and sunspots are correct methods for use and for testing these relationships?

Figure 5 presents the spectrum of series of annual sunspot numbers and Figure 6 the average spectrum of annual precipitation series over a region of the United States. The other five regions of the United States show similar spectra [8]. Those who are acquainted with spectra should pose the question of how a process such as the annual precipitation process, with no special spectral density at the frequency of 11.3 years, could be related to the annual number of sunspots, with a high spectral density at this 11.3 year cycle? The spectra of annual precipitation process for many series all around the world have none or a very small bump at the same frequency of 11.3 years. Besides, looking at the 22 year frequency, both variables, the annual number of sunspots and the annual precipitation series, do not show significant spectral densities in comparison with those of other frequencies, except for the frequency of 11.3 years and of the very low frequencies of sunspot numbers.

An approximate rule, useful in practical studies of interrelationships of random variables, is that if the simple or the multiple correlation and regression analyses, for various functions of correlative association, do not show significant relationships, the chances are very small that the methods of physical and other relationship investigations would produce very different results. The outcome of simple and multiple regression and correlation analyses are indices of relationships to be obtained by the other types of investigations.

Also important in the search of relationships between the terrestrial and extraterrestrial variables is the problem whether the solar radiation constant is a real constant, or whether it varies over time. Similarly, some doubts exist whether or not the sunspots are strictly a periodic phenomenon over a

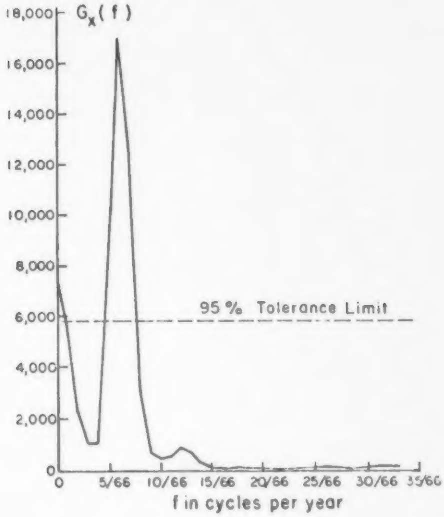

Figure 5. Variance spectrum versus frequency of the series of annual sunspot numbers.

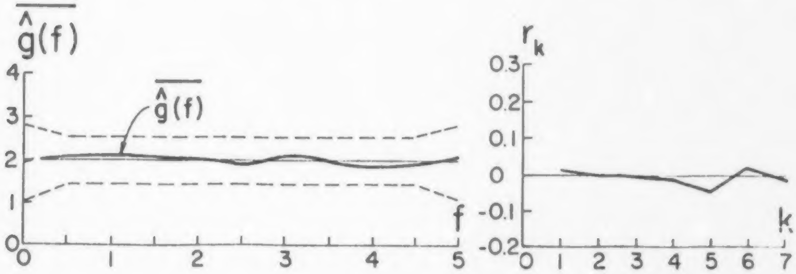

Figure 6. Average variance spectrum (left) and average correlogram (right) of the annual (homogenous) precipitation series of northwest area of the United States (area No. 5 between longitudes 94° and 85°, and latitude 36.5° and Canadian-USA border), as average graphs of 231 precipitation station series.

long time, because of some claims that they did not occur for a significant period of time in the Middle Ages, with the "little ice age" cold weather being a result. This explanation would then imply that the lack of a sufficient number of sunspots, or a long solar quiescence, is the cause of cool weather over the entire earth's surface, as well as the cause of droughts (assuming that cold weather is paralleled by the decrease in precipitation).

3.4 Methods of Forecast by Using Shifting Patterns

Several conjectures imply that movements of lows and highs of pressure in the atmospheric circulation follow patterns which change in position causing middle-range and long-range fluctuations. If the changes in these patterns could be forecast, it then would become feasible to use them for the forecast of droughts. First, it is necessary to find the reliable methods of forecasting whether, and when, the changes in patterns of lows and highs of pressure will occur, as well as how long the new patterns would last before they could be related to or used for the forecast of droughts (if relationships between pattern changes and the drought variables are found to be significant).

3.5 Methods of Forecast by Analogy

Another method for short-range, middle-range and long-range climatic forecasts, and indirectly for drought forecasts, is based on the comparison of present time patterns of various weather and oceanic variables with the similar patterns that have been observed in the past. The expectation is then that the evolution of present patterns into the forthcoming patterns will be similar to evolutions observed in the past. This comparison leads to the forecast. This approach is based on the indirect inference that complex physical processes of the present would determine the outcomes of these processes, as a feasible forecast, because it happened several times in the past.

This approach requires the assembly of all the information which may affect the evolution of present weather patterns. The method may be somewhat similar to the approach of shifting patterns in lows and highs of the atmospheric pressure. What is being inferred by the comparison of patterns is that the sufficient knowledge is not available on physical systems and their processes, so that the outputs of these systems and realizations of processes integrate these physical properties. Then, they can be compared for the purpose of their extrapolation. Regardless that this method is used for short-term forecast in several countries, no firm evidence is yet available as it concerns its feasibility for middle-range and particularly for long-range drought forecasts.

3.6 Methods of Forecast Based on Time Series Analysis

Some methods for long-range forecasts are based on past observations of time series. One such method uses the Fourier series analysis of available time series of weather and hydrology variables. These series are decomposed into individual periodicities, usually designated as "hidden periodicities", because no reliable physical explanations are available or found as the causes of these periodicities. Those ordinates of periodograms or spectral graphs, which show somewhat larger values than the average of smoothed spectral values, are inferred in this method as hidden periodicities. By extrapolating the identified hidden periodicities with relatively higher amplitudes into the future, the recomposed series result as almost-periodic forecast series because of noncommensurability of frequencies of these spectral densities. This approach of hidden periodicities has been very much in fashion with many geophysicists, both before the First World War and between the two World Wars, and still continues sporadically to be used. However it seems that it has been one of the most spectacular historic failures in producing long-range forecasts of climatic variables in general and of drought variables in particular.

The basic process of annual precipitation, annual runoff and other annual variables that define droughts are either independent stochastic processes (like precipitation, as shown in Figure 4) or stochastically dependent processes (like ocean temperature of Figure 3). Therefore, the approach that either an independent or a stationary dependent stochastic process can be decomposed in hidden periodicities of significant amplitudes, and then recomposed for forecast purposes, must have failed, at least by the principles and valid tests of probability theory, stochastic processes and mathematical statistics.

Figure 4 shows an independence of annual precipitation series of an area in the United States, while Figure 7 shows a dependence of annual river flows of rivers in this same area. Only the storage of water in river basins (as well as the process of evaporation) may be the causes that produce the difference in spectra of Figures 4 and 7, or from an independent to a dependent stochastic process.

3.7 Combination of Forecast Methods

No approach seems to have yet been developed that can combine two, three or more of the above methods for the purpose of increasing the feasibility of drought forecast. The future may eventually show that combinations of methods may become a feasible way of increasing the outlook for the long-range drought forecast, at least for a couple of months in advance, in comparison with the use of any one method separately. It is logical to expect that several methods properly applied and combined would increase the power of forecast beyond the accuracy of any one particular method.

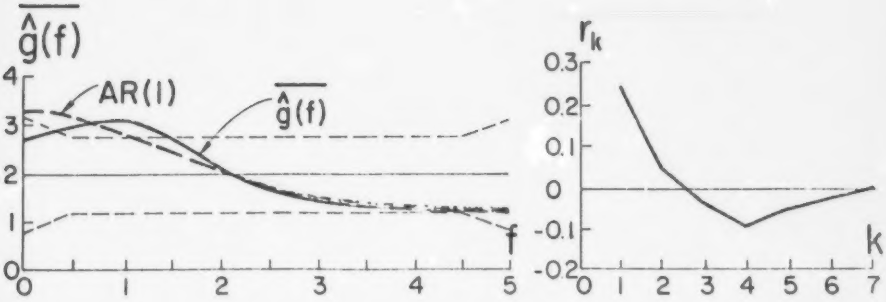

Figure 7. Average variance spectrum (left) and average correlogram (right) of the annual runoff series of northwest area of the United States (same area as for Figure 6), as the average graphs of 88 runoff station series.

4. CONCLUSIONS

From the above condensed review of methods of long-range drought forecasts, it seems that a logical conclusion should be drawn, namely that no method that is available at present can produce a feasible long-range forecast of droughts, say for several months or a couple of years in advance. This statement excludes the middle-range and long-range forecasts that do include the anticipated melting of snow already observed on the ground, or the expected outflows of already accumulated water in river basins, because the stored waters in liquid and solid states may be the only feasible background information for a long-range drought forecast of time lags of several months. Because of limitations in long-range forecast in general, the stress on investigations should be on the predictability of droughts in probabilistic terms. Spending time and funds in research and investigation should then be properly balanced between the long-range drought forecast by whatever method it may come out to be promising, and the probabilistic drought prediction information extracted from the past observations of drought defining random variables.

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Drought Prediction and Extended Forecasting

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1. Introduction

To me, drought is mostly a prolonged period of very light precipitation, but it is only one extreme of the entire precipitation spectrum. The main interest here in the Canadian prairies, as far as I can see, is in agricultural drought, which really means abnormally low soil moisture. If we neglect streamflow and snowmelt, soil moisture is determined by precipitation minus evaporation, and evaporation depends in large part on temperature. So we're going to discuss both precipitation and temperature. Furthermore, drought is very specific, very dependent on the particular locality and the particular month or season under consideration. A drought in the wettest part of Canada or the United States would be quite different in precipitation than a drought in Nevada or Arizona. These things lead me to the conclusion that drought prediction is really just an extreme case of extended weather forecasting. That's what I'm going to talk about today, drought prediction and extended weather forecasting.

2.Extended Forecasting

Monthly and seasonal forecasts are prepared regularly by the Climate Analysis Centre (CAC) of the U. S. National Weather Service (NWS). Let me give you a brief description of the procedure involved in preparing extended forecasts at the CAC. The first step is to predict the large scale circulation pattern over the entire northern hemisphere. The second step is to translate this circulation pattern into surface weather. The third and final step is to convert the whole thing into probabilities. The weather forecasts are issued in probability terms, and that is the best way that any uncertain event like monthly or seasonal precipitation should be expressed.

The first step is done largely subjectively by combination of several different methods. First, they (CAC) use local persistence of heights at the 700 mb level, approximately 3000 meters high. It is the lowest level at which you can clearly see the jet stream and sinusoidal waves, the troughs and ridges that dominate the atmospheric circulation. They apply simple linear regression equations, derived from about 40 years of data at each grid point covering the northern hemisphere, on a month by month basis. This produces a regression type forecast of what the expected height anomaly at each point will be. Since weather forecasting is an initial value problem, they always use the latest observed month or season as their starting point.

CAC also uses other methods to predict the circulation. They try to see where the indications are strongest, where the correlations are highest, where the forecast height anomaly is greatest. They are looking for an anchor or a key area on which to base their forecast. Knowing that, they then go into their catalogue of teleconnections which shows, for example, what to expect in the United States when there is a strong 700 mb height anomaly around 150 degrees west and 50 degrees north (where ship Papa used to be). If you have a strong positive anomaly there, you are apt to get a strong negative anomaly in the western United States and a strong positive anomaly on the east coast (Bermuda High). Similar types of teleconnections are used for other areas.

First, CAC carefully analyzes the latest situation. They follow the movement of 700 mb height anomalies from place to place, from month to month, and from season to season over the whole northern hemisphere. They know what they're starting with, what the latest trends are, and what extrapolation gives for the future location and intensity of the anomaly centers. In addition they use analogues (similar situations in the past), but more for the seasonal than the monthly forecast. ENSO has been considered more and more in the last few years, mostly for the seasonal forecasts. Other features of sea surface temperature in the Pacific, both in the extratropics and in the tropics, are also used. One of the most important tools for the monthly forecast is the medium-range numerical prediction made by the large computer models, which shows some daily forecast skill all the way out to ten days. CAC is using this more and more to get a good start on the coming month, and it is really very hard to beat. Probably in the future, numerical prognoses will handle 90% of the monthly forecasting problem, just as they have taken over the five-day forecast operation in the last ten years. But chances are, in view of the limits of daily predictability, that medium-range models will not help with the seasonal forecast.

I don't want to say anything further about step 1 because it's too subjective for my liking and has been described in detail elsewhere. My main research has been in step 2, which is now almost completely objective, that is, translating the circulation pattern into its accompanying surface precipitation and temperature anomalies. CAC now has an operational system for specifying the surface temperature over most of the northern hemisphere. Separate studies were made for the United States, Canada, Alaska, Europe and Asia. Starting with the prognostic 700 mb circulation, the computer routinely produces a prognostic temperature pattern. In precipitation we have not yet advanced this far; objective specifications are only produced for the United States.

Finally, the third step, the issuing of probabilities, is a recent advance, and, I think, a good one. Verification statistics, based on many previous forecasts, and forecaster confidence are used to determine the probabilities to be assigned to each region. The forecasts are expressed in terms of three classes: above normal, near normal, and below normal. Since the forecasts of near normal conditions are poor, and since this class is expected to occur about 40% of the time, it is assigned a constant probability of 40%. Because it is easier to forecast extremes, either above or below normal, that's really what CAC forecasts in probability terms (ranging from 10% to 50%).

Now I want to show you about specification of temperature and precipitation, mostly in this area. Then I will say something about the greenhouse effect at the very end.

3. Temperature Specification

Figure 1 is a map showing the 55 stations in Canada for which we were able to get 30 years of temperature data. The basic period for this study, 1951 to 1980, coincides with the current World Meteorological Organization (WMO) normal period. Since Regina is in the middle of the Canadian prairies, we'll talk about it mostly.

A couple of years ago, I did a job for the Canadian Climate Center (CCC) on specifying monthly mean temperature for these 55 cities, and they wanted me to use heights at 500 mb (6km), instead of 700 mb. The potential predictors were heights (for the same 30-year period) at the 110 grid points shown in figure 2. The network covers a fairly large area, but with higher resolution (more points) in North America. Because my previous work was done at 700 mb, I wanted to see how 500 mb would compare. Figure 3 shows the reduction in variance (RV or multiple correlation squared), averaged over 55 stations, yielded by either 700 mb or 500 mb heights for a given number of terms. I used a forward selection procedure of multiple regression called screening. The first term picked has the highest simple correlation with temperature out of all 110 heights considered. The second height selected offers the most additional independent information, but it increases the RV by a smaller amount. Then the amount of improvement peters out, so the trick is to know when to stop adding variables. This figure is for the average of 12 months. I have separate graphs for all four seasons, and they are all very similar. There is a small but consistent improvement obtained by screening heights at 500 rather than 700 mb. This is an interesting result that deserves more research, even though the circulation patterns in nature are similar at the two levels.

Figure 4(a) shows the correlation of Regina surface temperature with 700 mb heights for winter. Regina is located at the star. For the winter months (December, January and February) for the 30 years, the monthly mean temperature departures from normal at Regina were correlated with the simultaneous 700 mb height departures at each grid point. The resulting pattern is typical of stations in the United States, Europe and Canada. The maximum correlation coefficient (+.63) is close to the station, but there is another important area about a half wavelength upstream. It's always a negative correlation, and here it is -.60 over southwestern Alaska.

Figure 4(b) was obtained by multiplying the correlation coefficients of figure 4(a) by the standard deviation of height at each point. If you want to interpret the pattern in terms of the anomalous flow, it is not quite accurate to do it from the correlation field alone. It is better to use the field of correlation multiplied by standard deviation because the latter varies greatly in space. This procedure changes the relative magnitude of the centers of maximum and minimum. In the Gulf of Alaska and the Aleutians, the standard deviation of height is at a maximum for the whole northern hemisphere, but on the continent it's quite small. So where the two correlation centers were almost equal in magnitude in figure 4(a), now the western center is twice as large. Figure 4(b) gives the most favorable 700 mb pattern for abnormally warm weather in Regina: a positive height anomaly center over the western United States and a negative center over southwestrn Alaska. If we assume the negative and positive anomaly centers to be like sea level lows and highs, then the flow curves anticyclonically around the high and cyclonically around the low. So you can see warm, moist air coming in from the Pacific, plus downslope flow over the Rockies. This encourages warmth in Regina and the whole prairie region. Since the correlations are linear, the reverse situation holds for below normal temperatures. This gives you some understanding of what kind of circulation patterns go with abnormal heat or cold.

Table 1 shows how we pick a regression equation to use at Regina for specifying temperature from 500 mb heights in the winter months. Step zero just shows the standard deviation of temperature at that station (3.84°C). The first height selected is located at 50° north 110° west, near Regina, which is at 50°-105°. Its regression coefficient is positive, as expected from the center of positive correlation in figure 4(a), and it explains 43% of the temperature variance. The second height picked is close to the upstream negative correlation of figure 4(a) and is at 70° N, 160° W. in northwest Alaska. It increases the RV by 26%, a very significant amount, and raises the cumulative explained variance to 69%. The third term picked is something else we offer to the screening program; namely the previous month's temperature anomaly. In this way we take advantage of local temperature persistence where it exists. Here temperature makes a pretty good contribution, 4%, and its sign is positive because of local persistence. The fourth term listed has a classical "F" test probability of only 96%. Since we look for 98% as the significance criterion, this term flunks the cut-off test. Therefore, we stop the selection process with a 3-term equation that explains 73% of the temperature variance and reduces the standard error to 2°C. We know that the more terms you put into a multiple regression equation with a small sample size like this (90), the greater the danger of statistical instability, so you're better off with a simple equation.

TABLE 1: Summary of the forward stepwise regression statistics obtained for Regina, Saskatchewan (50.4°N, 104.7°W) during winter months. The star shows the final equation selected for specifying monthly mean temperature anomaly from anomalies of 500 mb height field and previous month's temperature.

Step No.	Predictor selected	Reg. Coeff. upon entry	Probability (F-test)	Added RV(%)	Cumulative RV(%)	Standard error (°C)
0	0	0	0	0	0	3.84
1	50N, 110W	+.050	100.0	42.78	42.78	2.91
2	70N, 160W	-.029	100.01	25.87	68.65	2.15
3*	prev.temp.	+.219	99.96	4.34	72.99	2.00
4	20N, 70W	+.026	96.26	1.35	74.34	1.95
5	20N, 150E	-.021	90.73	0.85	75.19	1.91

Equations like those of table 1 were derived for 55 stations in Canada and 13 in Alaska for each month of the year. Figure 5 gives the geographical distribution of the mean annual reduction of variance using 500 mb heights and the previous month's temperature. The prairies have the highest RV of any region in Canada or Alaska, with values over 80% in most of Alberta for the whole year. On a seasonal basis, the distribution is not much different. In winter, figure 6 shows almost the same pattern as figure 5 except for the Arctic where values are lower. In the summer (figure 7), the RV is still 80% (or slightly less) in the prairies. But in the Arctic values increase from 50 to 75%.

A system like that discussed above is now used routinely to specify the monthly temperature in the United States. Figure 8 shows specified and observed temperatures for January, 1982, when CAC first started using this method. In this example, the equations were applied to the observed 700 mb height anomalies. If the heights had been forecast perfectly, the equations would give below normal temperatures all through the central United States (figure 8(a)), near normal on the east and west coasts, and one small pocket of above normal in Utah. Figure 8(b) is what was actually observed and is quite similar to figure 8(a). In practice, CAC routinely produces temperature forecasts based on forecast (not observed) height anomalies. Table 2 gives some of the verification figures, which of course, are not as good as those for figure 8. The official CAC outlook from 1981 to 1986 was in the correct class (above normal, below normal or near normal) 42% of the time, with a skill score of 12.7. The objective specification had about the same verification numbers. Persistence of last month's temperature had a skill score of 10.

TABLE 2: Verification of monthly mean temperature forecasts at 100 stations in the contiguous United States for 115 consecutive predictions made every 15 days for monthly and mid-monthly periods beginning Dec. 16, 1981 and ending Oct. 15, 1986.

Type of Forecast	Percent in Correct Class	Skill Score
Official CAC Outlook	42.0	12.7
Objective specification	41.9	12.8
Persistence of last month's temperature	39.4	10.0
Persistence of 1-5 day temperature forecast	41.0	11.5
Persistence of 6-10 day temperature forecast	41.2	11.4

So the forecasts are only slightly better than persistence. The last two entries in the table are for the five-day and ten-day forecasts, which are also very hard to beat.

Table 3 gives verification statistics using observed 500 mb heights for the Canadian stations, where we had quite a bit of independent data from 1981 to 1985. Amir Shabar of CCC ran this test. We had three types of equations. One was based on heights only, one on heights plus the previous month's temperature, and one on just persistence of the previous month. We used eight different verification statistics, and you can see that they gave consistent results. Persistence was always the poorest, heights only second and heights plus the previous month's temperature (the current operational system) best. Of course, we had very high scores here because we were assuming perfectly forecast heights. The average skill score was 47.5, a little higher than I obtained in a similar test.

You might wonder how the system performs regionally. Figure 9 gives the correlation coefficients between specified and observed temperatures for the above test. Notice again that the prairie region is highest of almost any place in Canada (0.9). In terms of skill scores (figure 10) , the same thing is true. The mean score of over 60 in that area is equalled only by one point on the west coast. Persistence (figure 11) doesn't do nearly as well, but it is pretty good again in the prairies. Thus our temperature specification equations give good results on both dependent and independent data and in both a research and operational mode.

TABLE 3: Comparative accuracy of monthly mean surface temperature anomalies in Canada specified from observed 500 mb height fields, with and without previous local temperature as potential predictor, in terms of eight different verification statistics. Scores obtained by simple persistence of last month's temperature are also listed. All results are averaged over 60 months and 51 stations on independent data from January, 1981 through December, 1985.

Statistic	Heights Only	Ht. and Temp.	Persistence
Percent correct (2 classes)	80.8	82.3	60.0
Percent correct (3 classes)	62.5	65.0	42.0
Mean absolute error (°C)	1.3	1.2	2.7
Root mean square error (°C)	1.6	1.5	3.3
Correlation between specified and observed temperatures	0.72	0.75	0.13
Correlation coefficient squared	0.50	0.57	0.02
Reduction of error (%)	48.0	52.4	-78.4
Heidke skill score (3 classes)	43.7	47.5	13.0

4. Precipitation Specification

Now I'd like to turn to precipitation. This element is hard to forecast on any time scale. One reason is that it is a small-scale phenomenon with very large differences across small distances. Therefore we used precipitation in 60 homogeneous climate divisions across the United States, with about 15 stations on average in each box of figure 12. For the same 30 years we used for temperature, the average monthly amount in each of these divisions was the dependent variable. Figure 13 shows the grid of 79 heights at the 700 mb level used as independent variables. Note that the points are much closer together than in Fig. 2 because precipitation is smaller in scale than temperature, but at the same time we don't have to go as far afield.

Figure 14(a) shows the correlation field during the winter months between 700 mb heights and precipitation for northern California. Here the maximum correlation is higher than anywhere else in the United States, with a center of -0.81 northwest of the reference area. Before jumping to any conclusions, remember that the correlation fields vary tremendously with different regions. For example, in Maine (figure 14(b)) the highest correlation is positive (+.63) and northeast of the division. When you convert the above results into anomaly maps, figure 15(a), shows that a deep low off the coast of Oregon, with its accompanying cyclonic southwesterly flow of moist Pacific air over the California mountains, is causing the heavy precipitation. In Maine (figure 15(b)), on the other hand, southeasterly anticyclonic flow from the moist Atlantic ocean is most favorable for heavy precipitation.

By the time of this study, we had become a little more sophisticated about how to select the number of terms in the multiple regression equation used for specification. We decided to use a Monte Carlo simulation, where we define the critical "F" value as the 95th percentile of all the "F's" obtained by screening randomly shuffled data 1200 times. The results (Fig. 16) show that the critical F depends on the number of potential predictors (M). It should be pretty obvious that if you offer a million predictors, one will give a high correlation, by chance alone. So the critical "F" values increase with increasing values of M. The classical "F" test gives critical values between 2 and 4 because it assumes an a priori hypothesis, but screening is different because it picks the highest correlation after the fact. That's why classical tests of significance don't apply to this kind of work. The Monte Carlo technique is pretty good, but it's not perfect. Therefore we still use some judgement in selecting our final equations.

Table 4 is a good example of a monthly precipitation specification equation for a climate division near Ashville, North Carolina in July. If you look at the latitude and longitude of Ashville, you see that the first point selected is just to its west and has a negative correlation. Its actual "F" of 33.7 exceeds the critical value (12) by a large amount. The second point picked is east of Ashville, and it is positive in sign. Again its "F" exceeds the critical value. We stopped there with just two terms because the next term is very remote, has questionable physical-synoptic meaning, and does not exceed the critical "F". The first two terms indicate clearly that stronger than normal southerly flow (of moist air from the Gulf of Mexico) favors heavy precipitation, while stronger than normal northerly flow (of dry air from Canada) accompanies lighter precipitation.

TABLE 4: Summary of the stepwise regression statistics obtained for western North Carolina (36°N, 83°W) in July. The final equation selected for specification is starred.

Step No.	Predictor selected	Reg. Coeff. upon entry	F value	Critical F	Probability (%)	Added RV (%)	Cumulative RV (%)
1	35N, 95W	-1.25	33.7	12.0	100.0	27.7	27.7
2*	35N, 65W	+0.60	12.1	8.0	99.9	8.8	36.5
3	50N, 150W	+0.15	5.0	6.6	97.1	3.5	40.0
4	55N, 45W	+0.17	2.5	5.8	87.9	1.7	41.7
5	25N, 115W	-0.40	2.0	5.6	83.5	1.3	43.0

The reduction of variance of all the precipitation specification equations for winter months is mapped in figure 17. The best results, over 70% explained variance, are found on the west coast of northern California, while values exceed 50% in parts of the Great Basin, Northeast and Gulf Coast. A pronounced minimum of RV is found over the Great Plains. Since we don't have any precipitation equations of this type for Canada, we can only extrapolate northward for the Canadian prairie region. Because only 10% of the precipitation variance is explained over North Dakota, it doesn't look like the prairies are going to be a very good area in the winter time. However, figure 18 shows values much better (40 - 50%) over Montana and North Dakota in the summer time, so the prairies may do pretty well on precipitation in that season. Everywhere else in the United States, the RV is worse in the summer because precipitation is small scale, convective and hard to predict.

One way to improve the results is to take larger areas, as illustrated for summer in Fig. 19. Instead of having 60 small climate divisions, a dozen coherent regions were developed by factor analysis. They each contain from 3 to 5 divisions, and the "x's" are their centers. To get an idea of your area in the prairies, we shall look at two regions: the northern plains centered in eastern Montana, and the central plains centered near the border between Kansas, Nebraska and Colorado. Figure 20 shows the correlations for the central plains in the winter, with a negative center in the southwest and a positive center over Hudson's Bay and Quebec. Figure 21 shows the corresponding height anomalies; the negative center in the southwest and the positive center over Quebec combine to produce heavy precipitation through southeasterly cyclonic upslope flow carrying moisture to the plains from the Gulf of Mexico. For below normal precipitation, just think of the -12 center in Fig. 21 as a plus 12 and the +27 center as a -27, and you see that anticyclonic northwesterly flow gives the driest conditions. If this circulation pattern lasts long enough and is even more intense, it will probably produce a drought in winter, not only in the plains of the United States, but also in the Canadian prairies.

A typical correlation field for the summer months, in the central plains is illustrated in Fig. 22(a), where the correlation is maximized right over the reference area (-.53). Fig. 22(b) converts Fig. 22(a) into a height anomaly map and shows that heavy precipitation is favored by a negative center over the north-central United States and a positive center off the British Columbia coast. If the signs were reversed, a warm high in the central United States and a deep low in the Gulf of Alaska could result in a strong drought. A pattern quite similar to this prevailed last spring and summer when very hot, dry weather covered the northern part of the United States and the Canadian prairies.

The correlation field and height anomaly map for the northern plains in winter (figure 23) are similar to the corresponding charts in the central plains (Figs. 20 and 21). However the pattern in the summer is a little different. Fig. 24(a) shows that the maximum correlation (-.67) is considerably higher in the northern plains in summer than it is in the winter. (-.36 in

Fig.23(a)). Figure 24(b) shows that a very strong cyclonic southwesterly flow is conducive to heavy rain in summer. If the signs were reversed, a strong anticyclonic northeasterly flow would result in dry weather and perhaps drought.

Table 5 gives statistics for our specification equation for monthly precipitation in the northern plains during summer. The first point picked is the one (with the highest correlation) just southwest of the target area. The second one is to the northwest, and the third (a little more questionable) is in the Gulf of Alaska. We have derived similar equations for each of the coherent regions and for each month. Figure 25 shows the average RV for the entire nation, month by month. The lower curve is for the 60 climate divisions, and the upper dashed curve is for the 12 coherent regions. The regions outperform the divisions every month of the year, with the biggest increase in the summer - the season of the smallest scale precipitation. This indicates that drought prediction should be made for a large scale area. The more you go to small local areas the less accurate you will be. Another source of improvement is averaging over longer time periods. Fig. 26 compares the explained variance for monthly and seasonal precipitation specification equations at four river basins in California and Arizona. Although the reduction of variance is only slightly better on the seasonal curve as opposed to the monthly, the results are consistent. Smoothing over time, as well as space, eliminates high frequency and small scale noise and thus improves specification of precipitation.

TABLE 5: Summary of the stepwise regression statistics obtained by screening percentiles of monthly precipitation in the Northern Plains (47°N, 106°W) during June, July and August, 1951 - 1980, as a function of the concurrent field of 700 mb height anomalies. The critical F-values were determined by a Monte Carlo procedure. The final equation selected for use in specification is starred.

Step	Grid point for height	Reg. Coeff. on entry	Added RV(%)	Total (RV)	Classical F-value	Prob. level(%)	Critical F-value	SE (percentiles)
1	45N, 115W	-1.287	45.4	45.4	73.1	100.0	11.2	21.7
2	55N, 125W	+0.356	6.2	51.6	11.2	99.9	7.3	20.5
3*	50N, 150W	-0.144	3.2	54.9	6.2	98.5	6.1	19.8
4	25N, 75W	+0.631	2.2	57.1	4.3	96.0	5.3	19.3
5	40N, 140W	+0.623	0.9	58.0	1.9	82.4	4.9	19.1

5. The Greenhouse Effect

In concluding I would like to say a few words about the greenhouse effect. The four largest and most sophisticated general circulation models now available in the United States all agree that, with a doubling of carbon dioxide (CO_2) in the atmosphere, average surface temperatures over North America will increase by 3 - 6°C. Because concentrations of trace gases other than carbon dioxide (e.g. methane) are increasing even more rapidly than CO_2, we will see the radiative effects of CO_2 doubling by the middle of the 21^{st} century. But precipitation, as usual, is very difficult to forecast, and the estimates of the four models disagree sharply, particularly in the summer. If you combine the expected changes in precipitation, temperature and evaporation, you can get pretty good estimates of the future soil moisture, which defines agricultural drought. Most models agree on an increase of soil moisture in winter in the Canadian prairie region, and the average amount of increase for CO_2 doubling is around 1 cm. But in the summer, the model concensus is that soil moisture will diminish in the prairie region - by about 1 cm on average. The reason is that even though precipitation may be unchanged or increased a little in the summer, the increased evaporation due to higher temperatures will cause the soil to dry out. Therefore, agricultural droughts as commonly thought of today may well become more frequent in the next century due to the greenhouse effect. I'm afraid it's going to be a rough time for our grandchildren and great-grandchildren.

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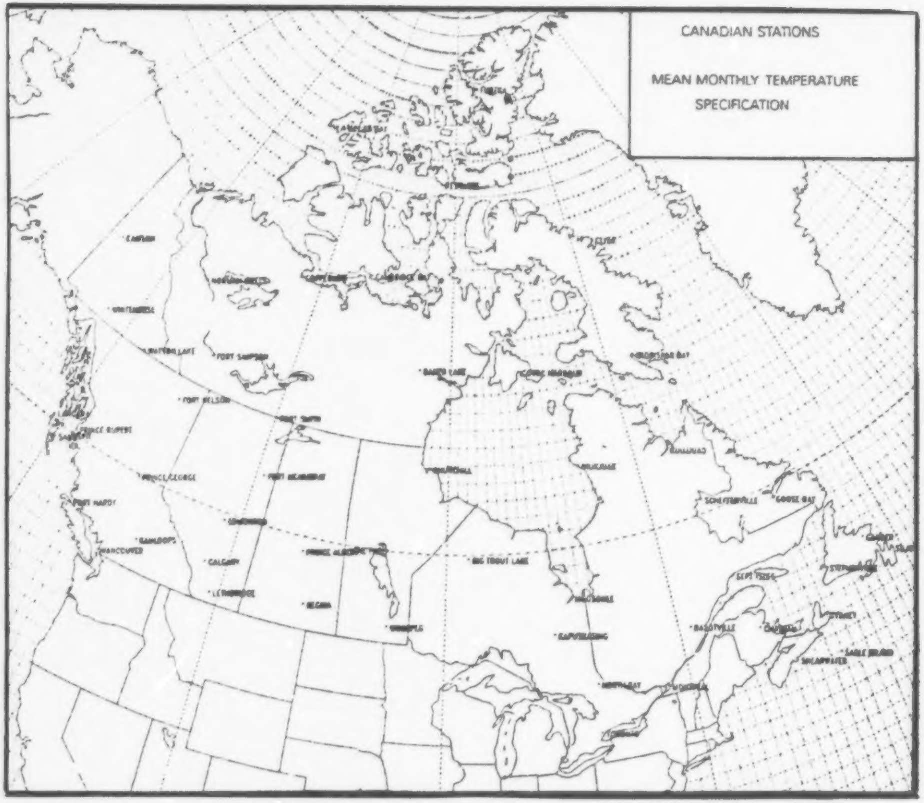

CANADIAN STATIONS
MEAN MONTHLY TEMPERATURE SPECIFICATION
CAMBRIDGE BAY
CLYDE
FROBISHER BAY
BAKER LAKE
CORAL HARBOUR
CHURCHILL
WATSON LAKE
FORT SIMPSON
FORT NELSON
FORT SMITH
PRINCE RUPERT
SANDSPIT
PRINCE GEORGE
FORT MCMURRAY
PORT HARDY
EDMONTON
KAMLOOPS
VANCOUVER
CALGARY
LETHBRIDGE
PRINCE ALBERT
REGINA
WINNIPEG
BIG TROUT LAKE
MOOSONEE
KAPUSKASING
NORTH BAY
MONTREAL
SCHEFFERVILLE
GOOSE BAY
SEPT ILES
BAGOTVILLE
STEPHENVILLE
GANDER
SYDNEY
SABLE ISLAND
SHEARWATER

Fig. 1. 55 surface stations used for specifying temperatures in Canada.

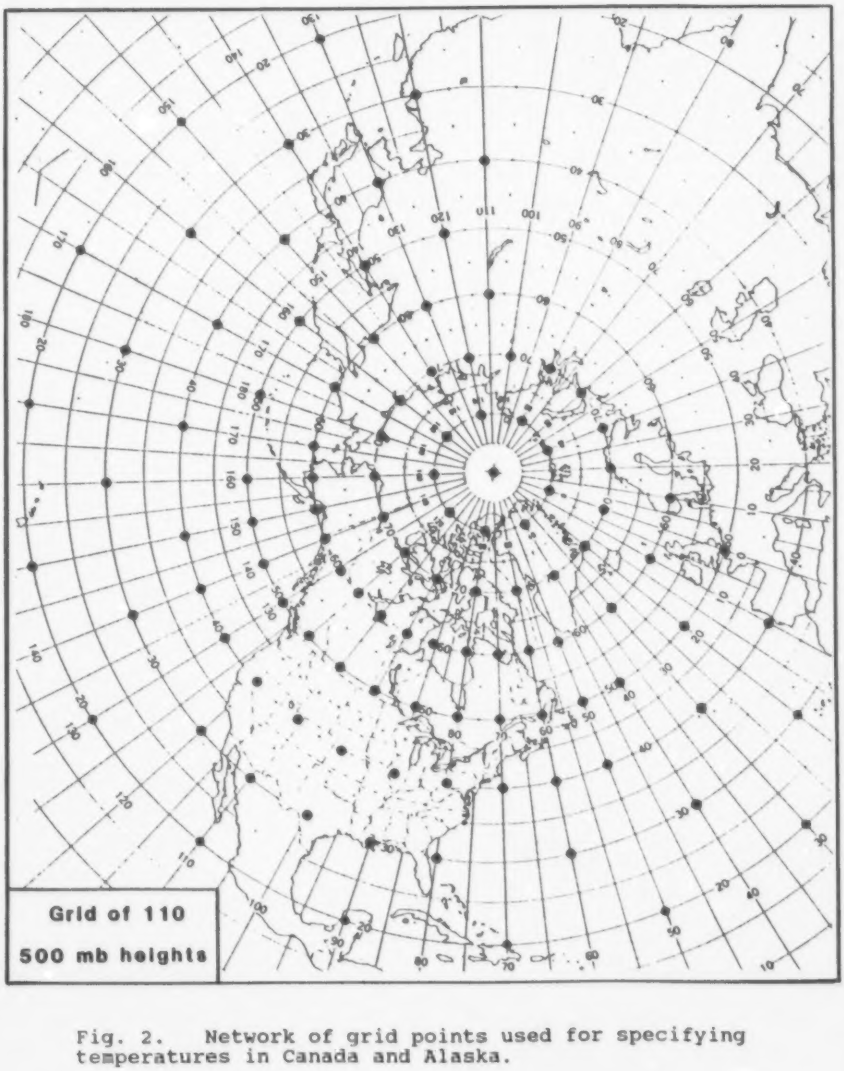

Grid of 110
500 mb heights

Fig. 2. Network of grid points used for specifying temperatures in Canada and Alaska.

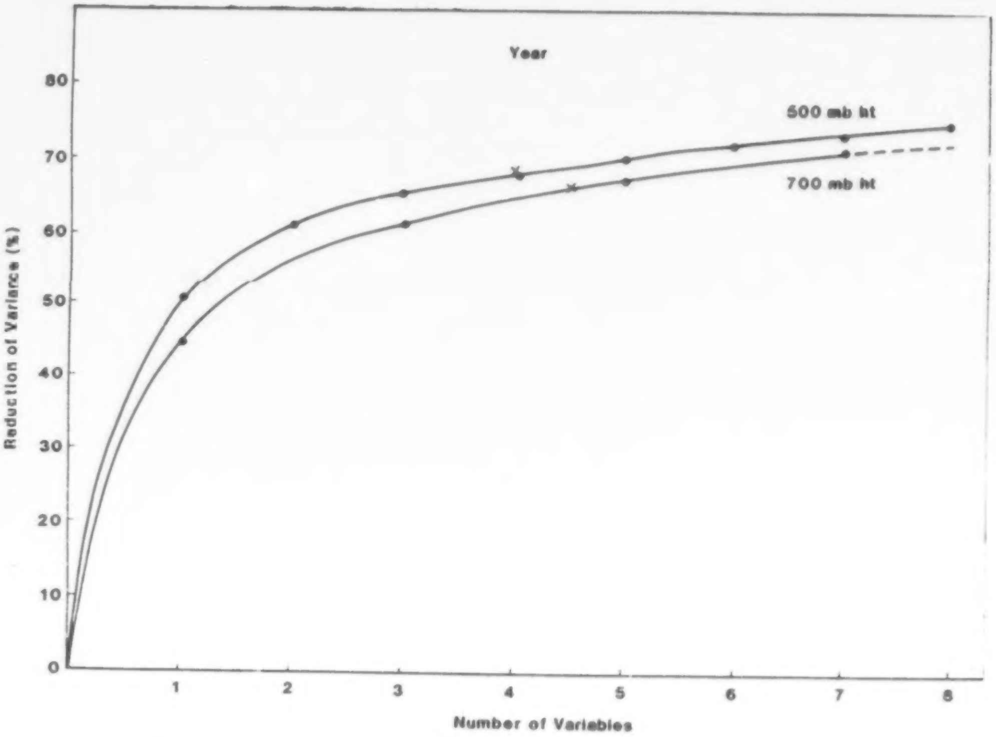
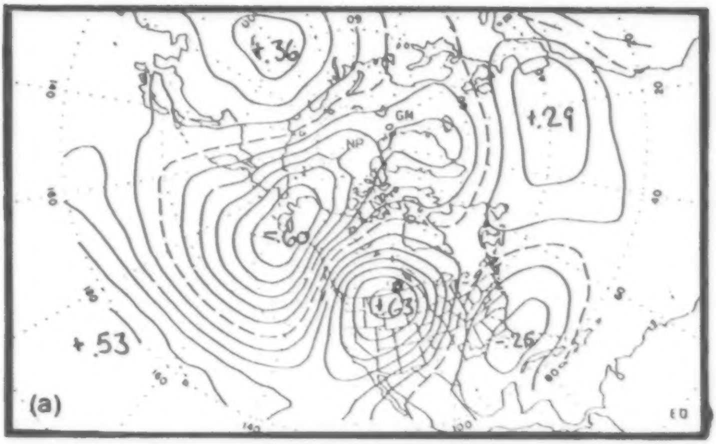
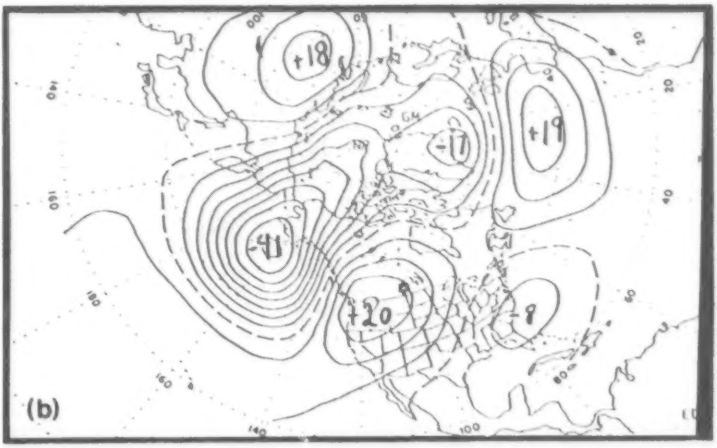


Fig. 3. Percent of monthly mean temperature variance at 55 surface stations in Canada averaged over all 12 months of the year, explained by screening concurrent height field at either 500 mb or 700 mb during 30-year period: 1951-1980.



REGINA, SASK CORRELATIONS WINTER MONTHS 1951 - 1980

SFC. TEMP. VS 700-MB. HT.



REGINA, SASK CORRELATION*STD.DEV. WINTER MONTHS 1951 - 1980

SFC. TEMP. VS 700-MB. HT.

Fig. 4. (a) Field of correlation coefficients between monthly mean temperature anomalies in winter at Regina (star) and concurrent 700 mb height anomalies. Isolines are drawn at intervals of 0.1 with zero line dashed.

(b) Height anomaly map corresponding to temperatures one standard deviation above normal at Regina. Isoline interva. is 5 meters, with zero line dashed.

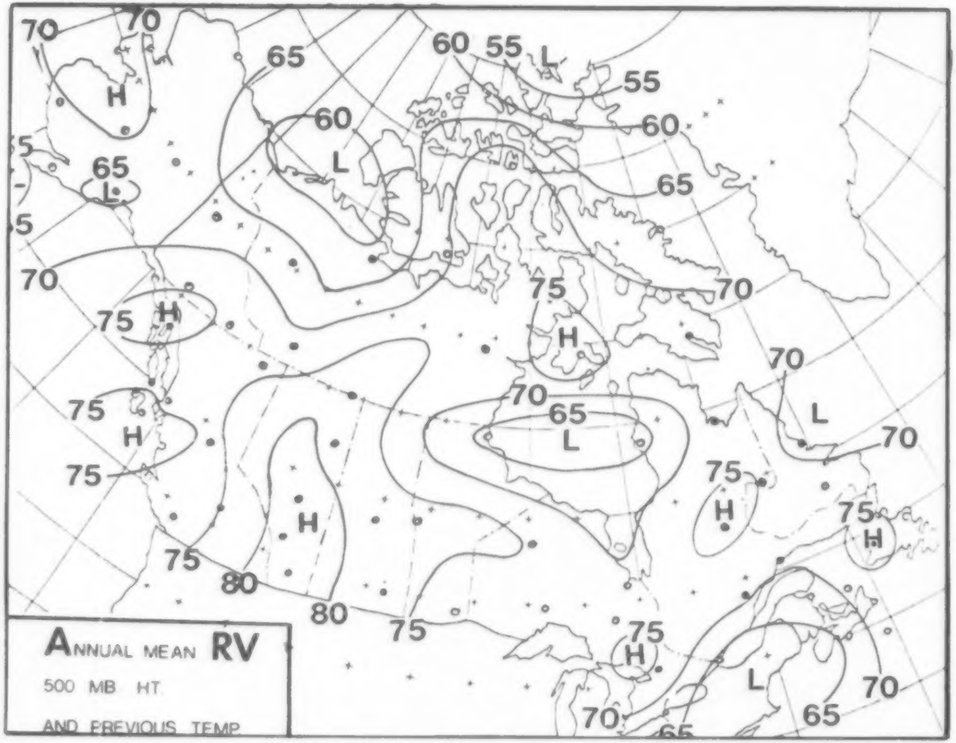

ANNUAL MEAN RV
500 MB HT
AND PREVIOUS TEMP

Fig. 5. Geographical distribution of mean annual reduction of variance of monthly mean surface temperatures obtained by screening 500 mb height field plus previous month's local temperature.

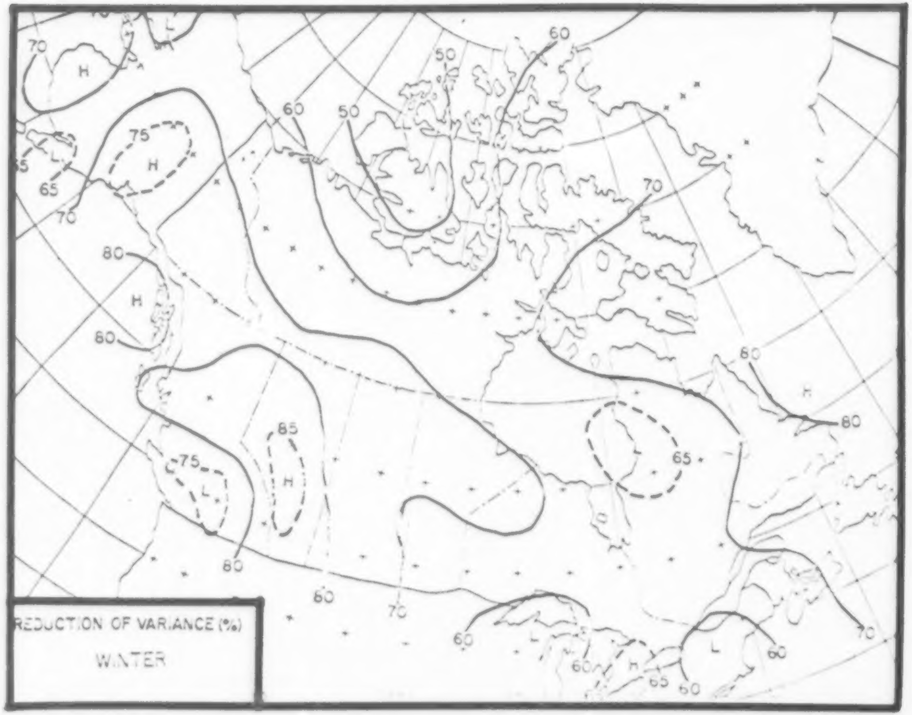

REDUCTION OF VARIANCE (%)
WINTER
70
H
L
75
H
65
70
80
H
60
60
50
50
60
70
80
H
80
65
85
H
75
L
80
60
70
60
L
60
H
65
60
L
60
70

Fig. 6. Geographical distribution of mean annual reduction of variance of monthly mean surface temperatures obtained by screening 500 mb height field plus previous month's local temperature for winter months only.

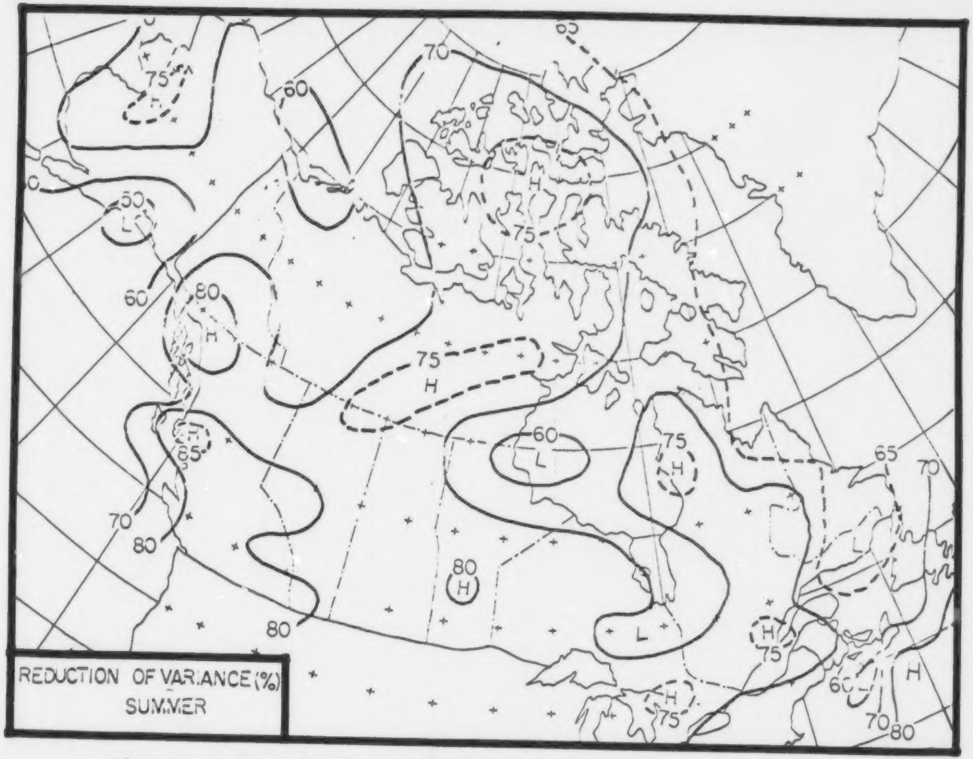

REDUCTION OF VARIANCE (%)
SUMMER
75
H
60
50
L
60
80
H
85
70
80
80
70
75
H
60
L
75
H
80
H
L
H
75
H
75
65
70
60
H
70
80

Fig. 7. Geographical distribution of mean annual reduction of variance of monthly mean surface temperatures obtained by screening 500 mb height field plus previous month's local temperature for summer months only.

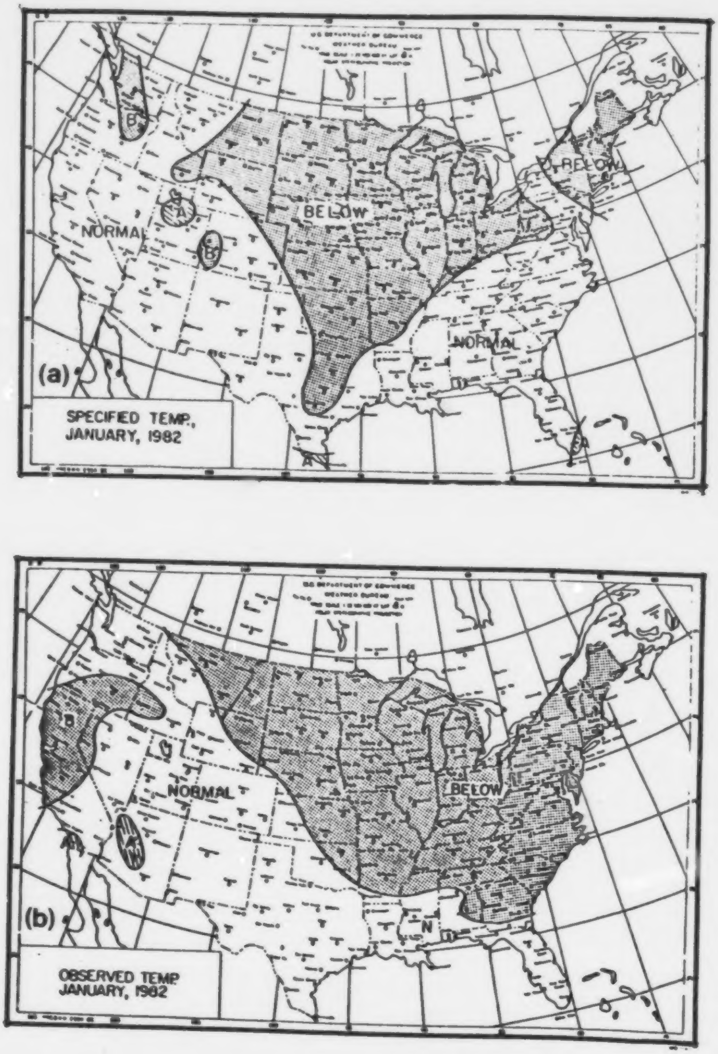

(a)
SPECIFIED TEMP.,
JANUARY, 1982
NORMAL
BELOW
BELOW
NORMAL
B
A
B
(b)
OBSERVED TEMP
JANUARY, 1982
NORMAL
BELOW
B
A
N

Figure 8.(a) Monthly temperature classes specified from observed 700 mb heights in January, 1982.
(b) Monthly temperature classes observed in January, 1982.

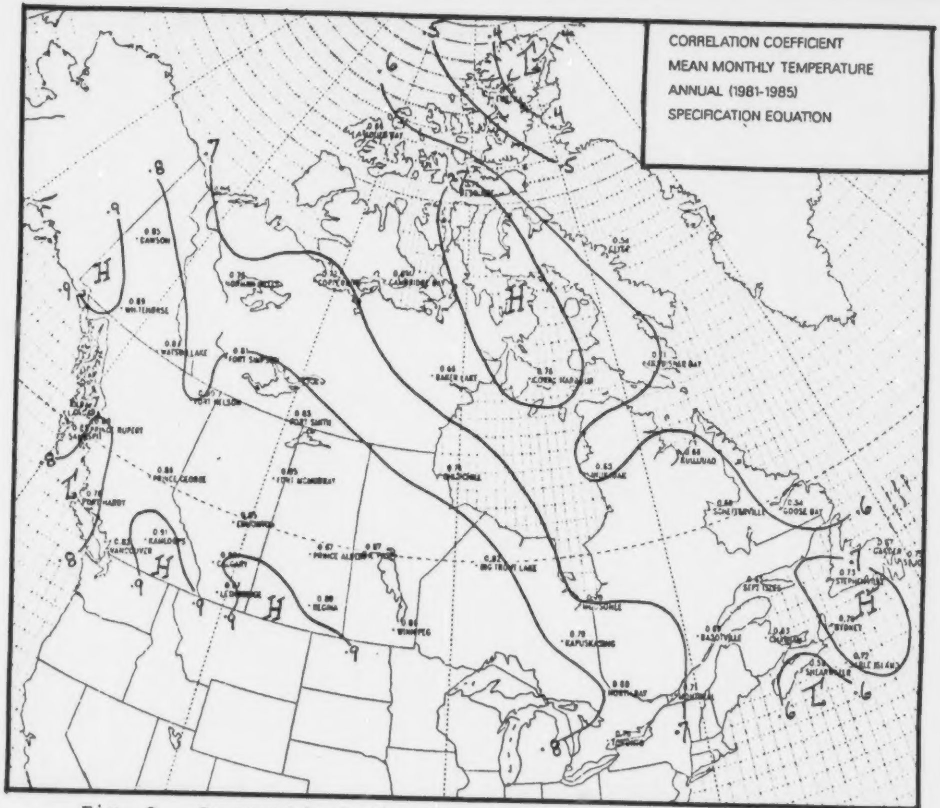

CORRELATION COEFFICIENT
MEAN MONTHLY TEMPERATURE
ANNUAL (1981-1985)
SPECIFICATION EQUATION
0.85 DAWSON
0.89 WHITEHORSE
0.87 WATSON LAKE
0.81 FORT SIMPSON
FORT NELSON
PRINCE RUPERT
SANDSPIT
0.78 PORT HARDY
0.88 PRINCE GEORGE
0.83 FORT SMITH
FORT MCMURRAY
0.91 KAMLOOPS
VANCOUVER
CALGARY
LETHBRIDGE
0.88 REGINA
0.67 PRINCE ALBERT
0.86 WINNIPEG
0.82 BIG TROUT LAKE
0.79 KAPUSKASING
0.80 NORTH BAY
0.71 MONTREAL
TORONTO
0.66 BAKER LAKE
0.76 CORAL HARBOUR
0.63
0.66 KUUJJUAQ
SCHEFFERVILLE
0.54 GOOSE BAY
SEPT ILES
BAGOTVILLE
0.83
0.57 GANDER
0.73 STEPHENVILLE
0.70 SYDNEY
0.72 SABLE ISLAND
0.58 SHEARWATER
CAMBRIDGE BAY
H
L
.4
.5
.6
.7
.8
.9

Fig. 9. Geographical distribution of mean annual correlation coefficients between specified and observed monthly mean temperature anomalies for 5 years of independent data.

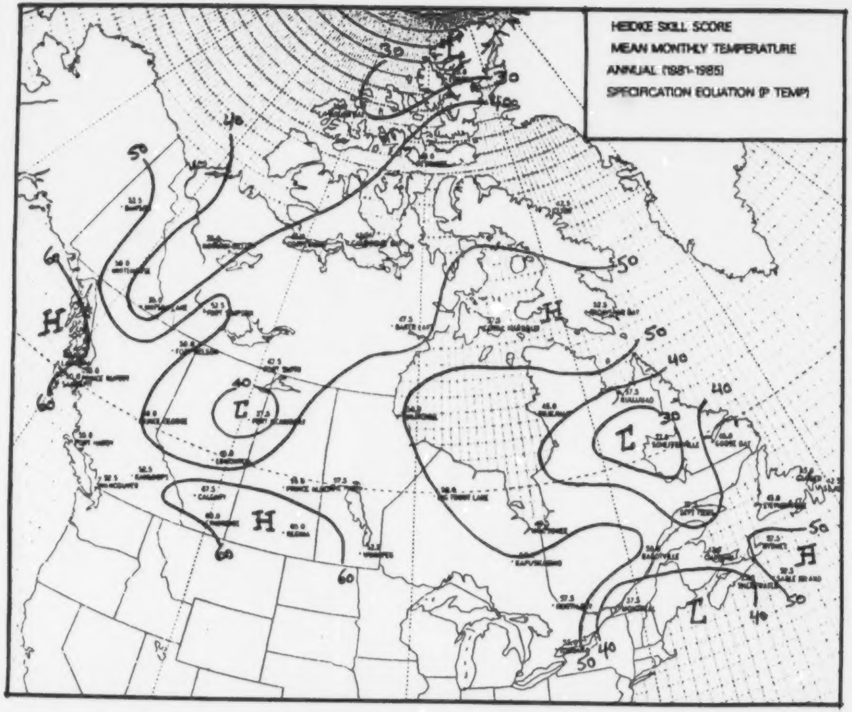

HEIDKE SKILL SCORE
MEAN MONTHLY TEMPERATURE
ANNUAL (1981-1985)
SPECIFICATION EQUATION (P TEMP)
30
40
50
60
H
L

Fig. 10. Geographical distribution of mean annual correlation coefficients between specified and observed monthly mean temperature anomalies for skill scores yielded by verifying specified temperatures.

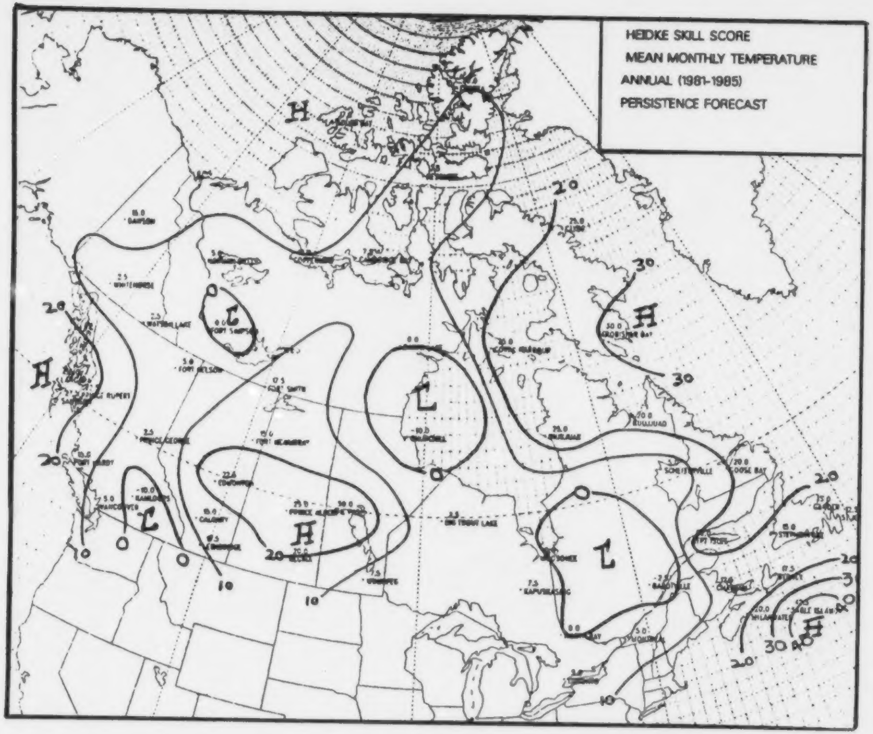

HEIDKE SKILL SCORE
MEAN MONTHLY TEMPERATURE
ANNUAL (1981-1985)
PERSISTENCE FORECAST
H
H
H
H
H
H
L
L
L
L
L
0
0
0
0
0
0
10
10
10
20
20
20
20
20
20
30
30
30
15.0 DAWSON
2.5 WHITEHORSE
2.5 WATSON LAKE
0.0 FORT SIMPSON
5.0 FORT NELSON
17.5 FORT SMITH
15.0 FORT MCMURRAY
2.5 PRINCE GEORGE
PRINCE RUPERT
10.0 PORT HARDY
22.5 EDMONTON
-10.0 KAMLOOPS
5.0 VANCOUVER
15.0 CALGARY
17.5 LETHBRIDGE
7.5 WINNIPEG
-10.0 CHURCHILL
2.5 BIG TROUT LAKE
30.0 FROBISHER BAY
20.0 KUUJJUAQ
25.0 INUKJUAK
20.0 GOOSE BAY
SCHEFFERVILLE
15.0 STEPHENVILLE
7.5 KAPUSKASING
MOOSONEE
-2.5 BAGOTVILLE
5.0 MONTREAL
17.5 SYDNEY
SABLE ISLAND

Fig. 11. Geographical distribution of mean annual correlation coefficients between specified and observed monthly mean temperature anomalies for skill scores obtained by assuming persistence of last month's temperature class.

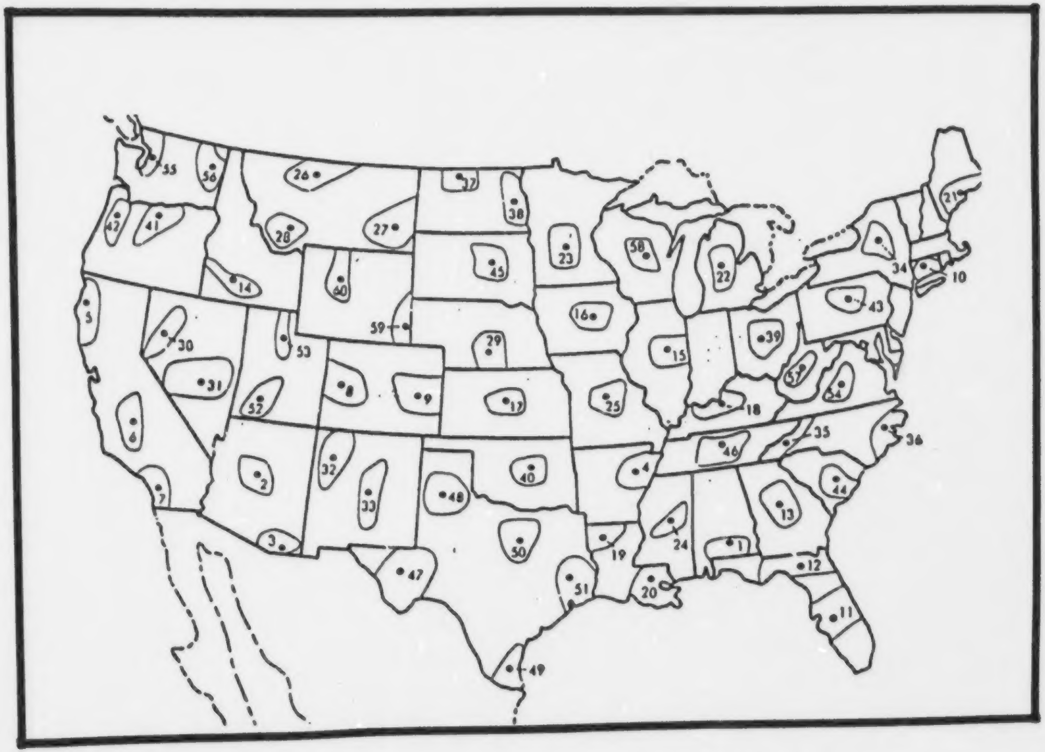

55
56
26
37
38
42
41
28
27
45
23
58
22
21
34
10
14
60
5
59
16
43
30
53
29
15
39
31
52
8
9
17
25
18
57
54
35
6
36
46
32
2
33
48
40
4
44
7
13
3
24
1
50
19
12
47
51
20
11
49

Fig. 12. Boundaries and centres (dots) of 60 climate divisions used for specifying precipitation.

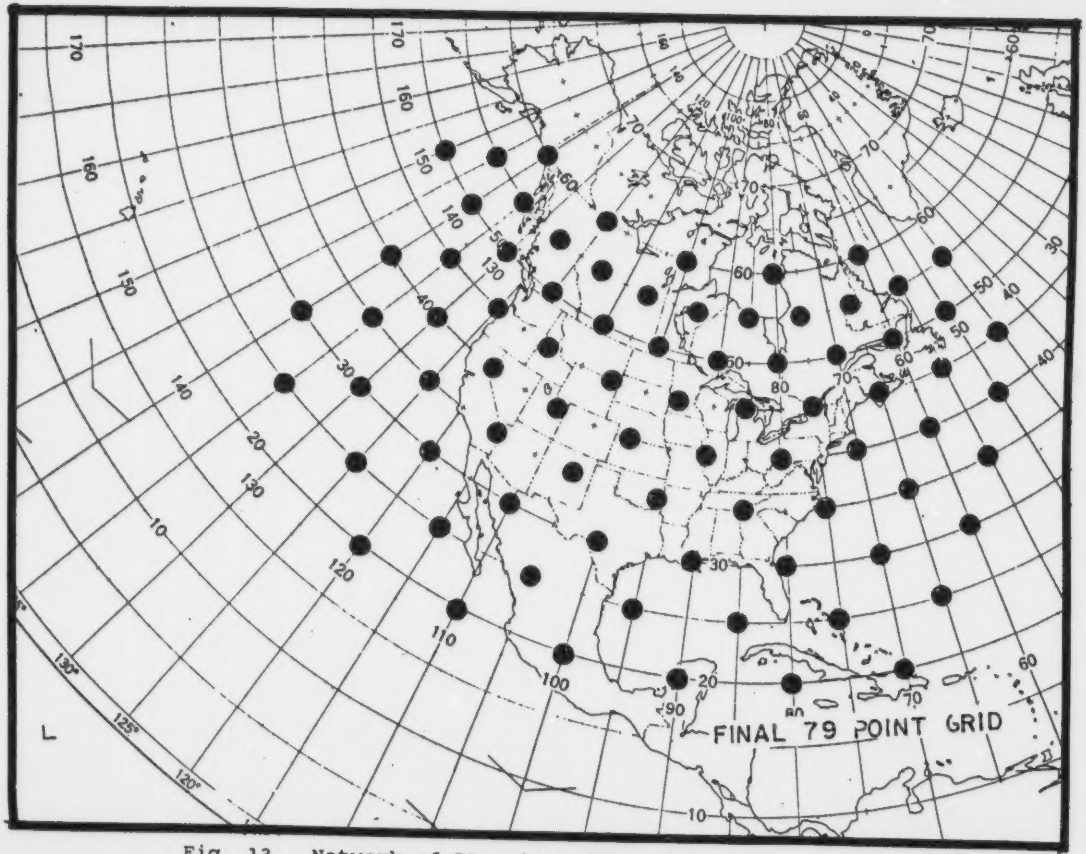
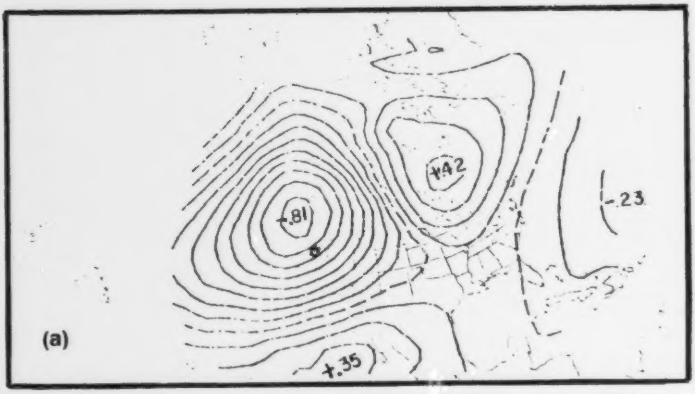
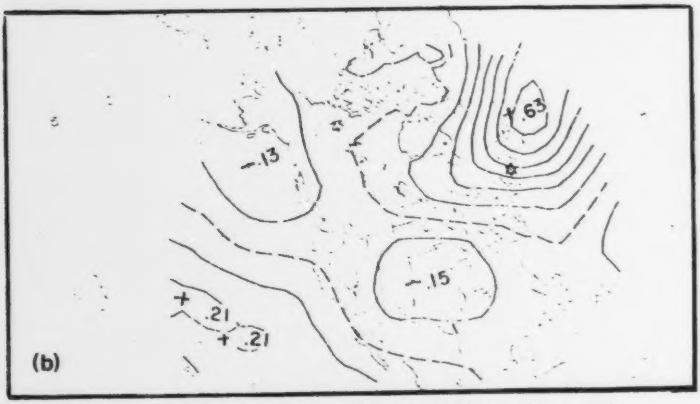

FINAL 79 POINT GRID

Fig. 13. Network of 79 grid points where 700 mb height was used for precipitation specifications.



CALIFORNIA CORRELATIONS WINTER MONTHS 1951 - 1980

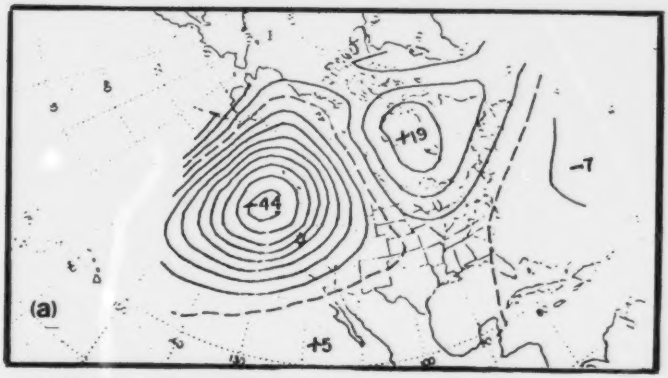
PRECIP. PERCENTILES. VS 700-MB. HT.



MAINE CORRELATIONS WINTER MONTHS 1951 - 1980

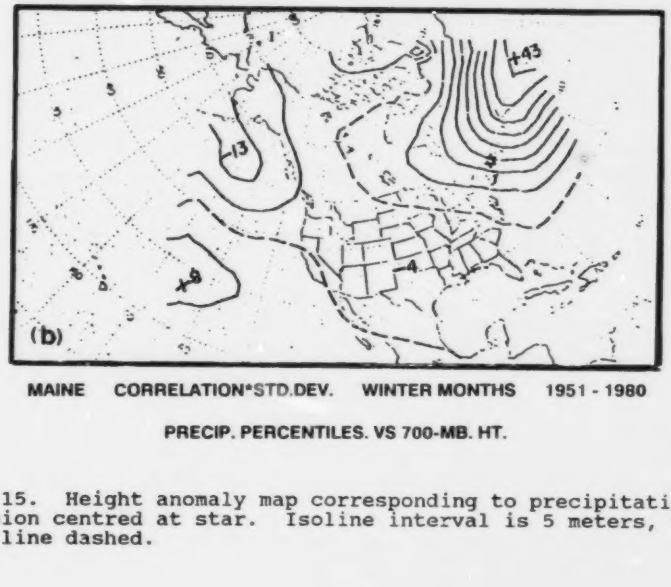
PRECIP. PERCENTILES. VS 700-MB. HT.

Fig. 14. Field of correlation coefficients between monthly precipitation in winter in division centred at star and concurrent 700 mb height anomalies. Isolines are drawn at intervals of 0.1 with zero line dashed.



CALIFORNIA CORRELATION*STD.DEV. WINTER MONTHS 1951 - 1980

PRECIP. PERCENTILES. VS 700-MB. HT.



MAINE CORRELATION*STD.DEV. WINTER MONTHS 1951 - 1980

PRECIP. PERCENTILES. VS 700-MB. HT.

Fig. 15. Height anomaly map corresponding to precipitation in division centred at star. Isoline interval is 5 meters, with zero line dashed.

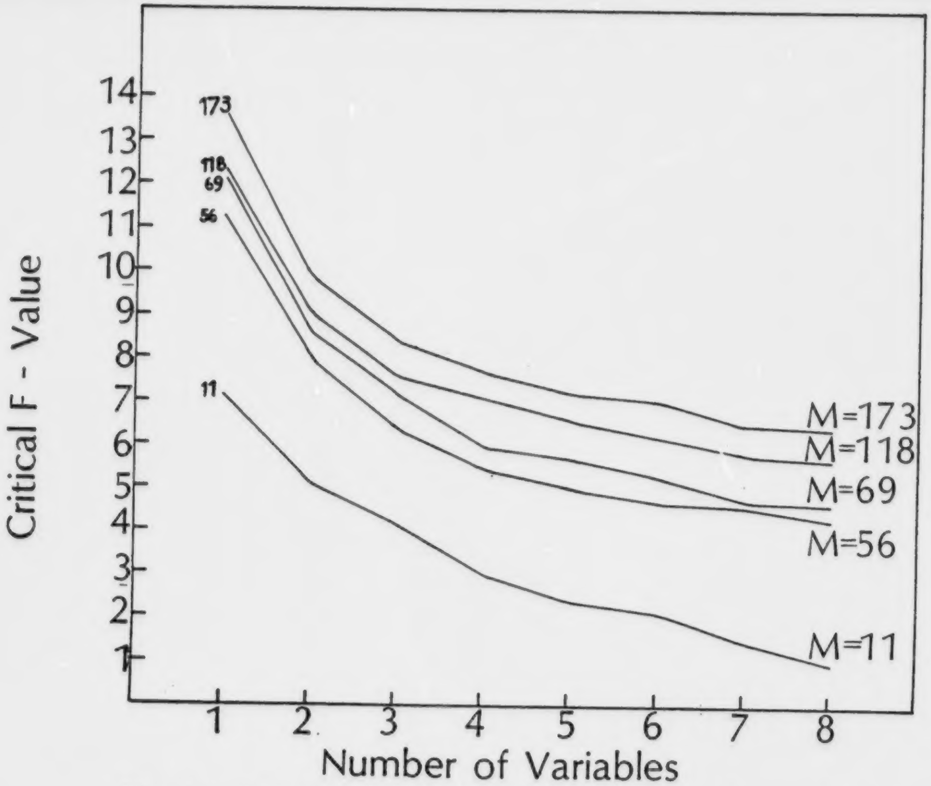


Fig. 16. F-values at the 95% significance level as a function of number of potential predictors being screened (M) and number of terms in the regression equation (abscissa).

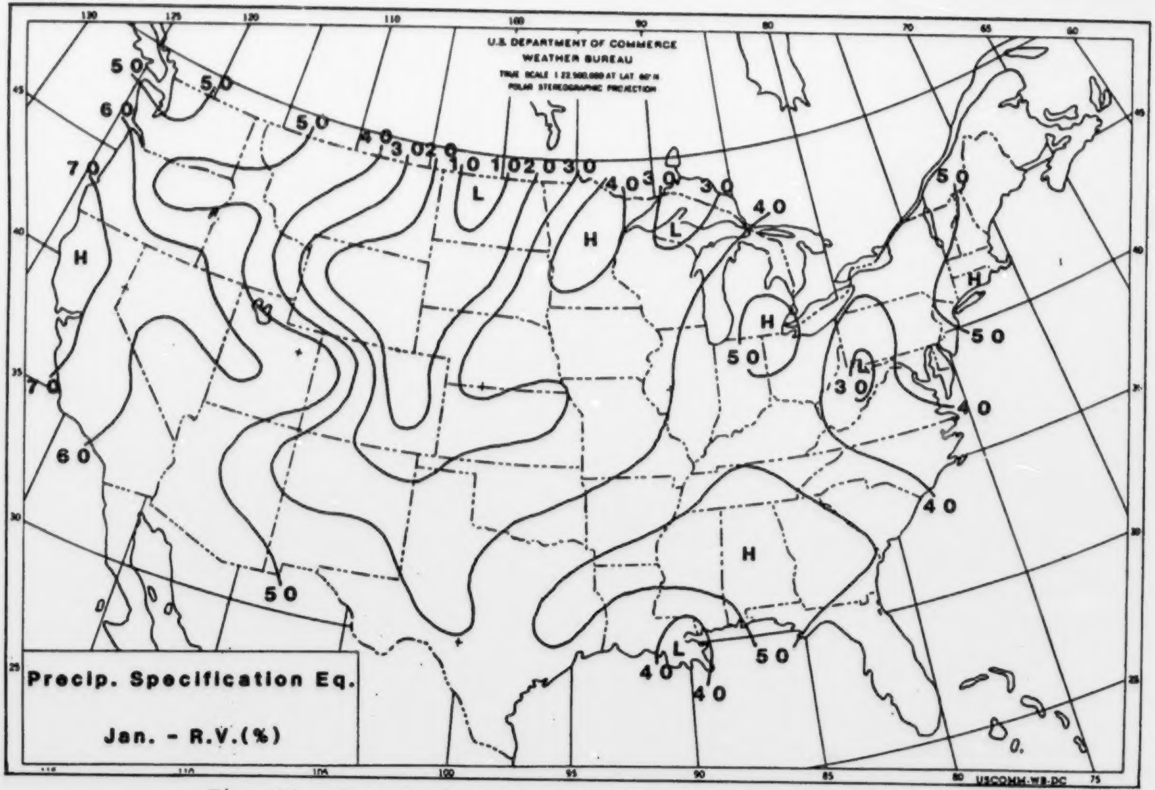

U.S. DEPARTMENT OF COMMERCE
WEATHER BUREAU
TRUE SCALE 1:22,500,000 AT LAT 60°N
POLAR STEREOGRAPHIC PROJECTION
Precip. Specification Eq.
Jan. - R.V.(%)
USCOMM-WB-DC
50
60
70
H
60
70
50
50
40
30
20
10
L
10
20
30
40
30
30
40
H
L
H
50
H
L
30
50
40
40
H
50
L
40
40
50
130
125
120
110
100
90
80
70
65
60
105
95
85
75
45
40
35
30
25

Fig. 17. Geographical distribution of reduction of variance yielded by precipitation specification equations during winter months (Dec., Jan. and Feb.).

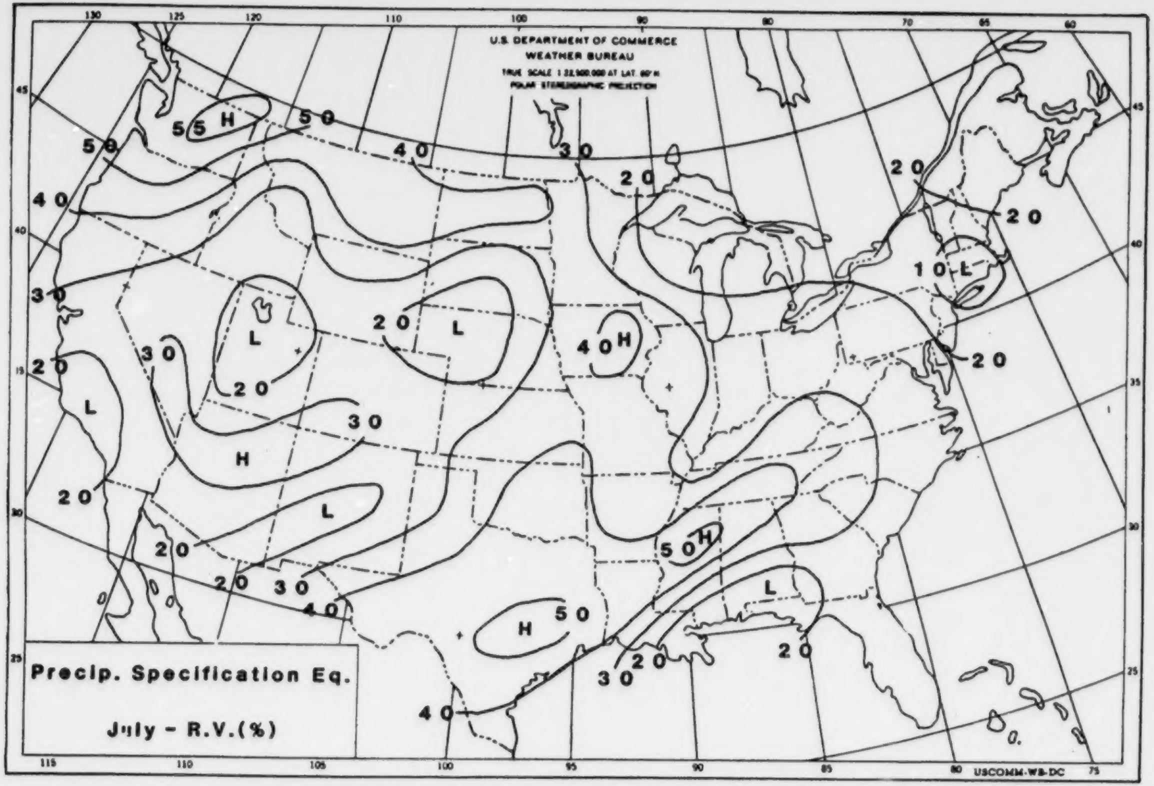

U.S. DEPARTMENT OF COMMERCE
WEATHER BUREAU
TRUE SCALE 1:32,500,000 AT LAT. 60°N
POLAR STEREOGRAPHIC PROJECTION
Precip. Specification Eq.
July - R.V.(%)
55 H
50
40
30
20
10 L
40 H
50 H
H 50
L
H
USCOMM-WB-DC

Fig. 18. Geographical distribution of reduction of variance yielded by precipitation specification equations during summer months (June, July and August).

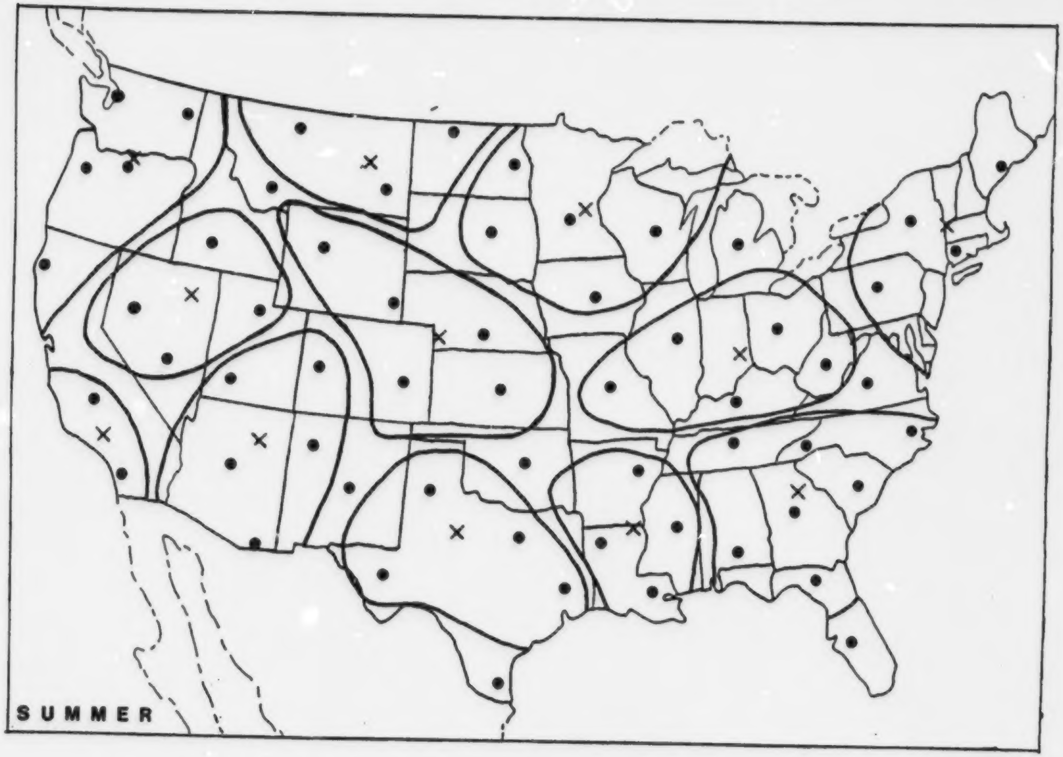
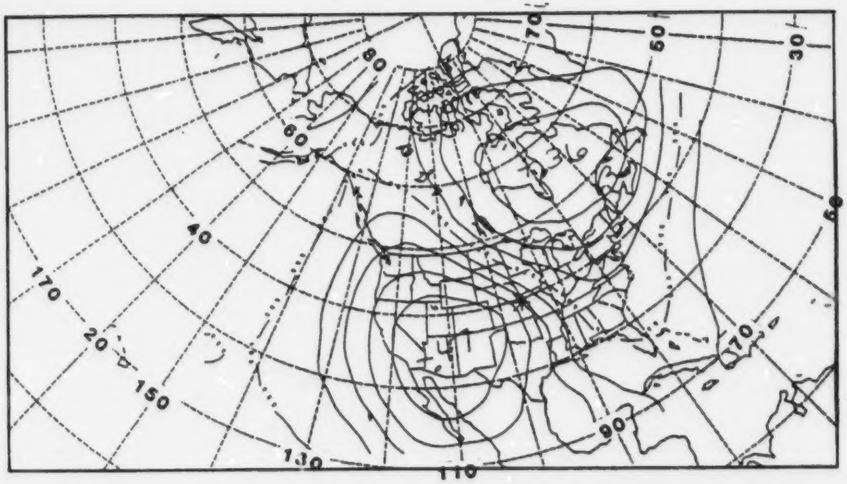


Fig. 19. Boundaries of coherent regions for monthly precipitation during summer (June, July and August). Regions are centred at crosses, divisions at dots.

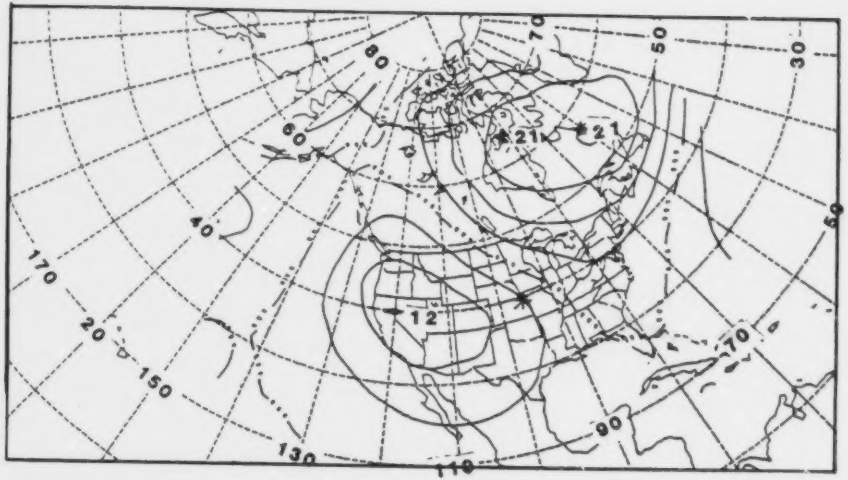

80
70
60
50
30
60
40
170
20
150
130
110
90
70

CENTRAL PLAINS CORRELATIONS

PRECIP. PERCENTILES. VS 700-MB. HT.

WINTER MONTHS 1951 - 1980

Fig. 20. Field of correlation coefficients between monthly precipitation in region centred at star and concurrent 700 mb height anomalies. Isolines are drawn at intervals of 0.1 with zero line dashed.

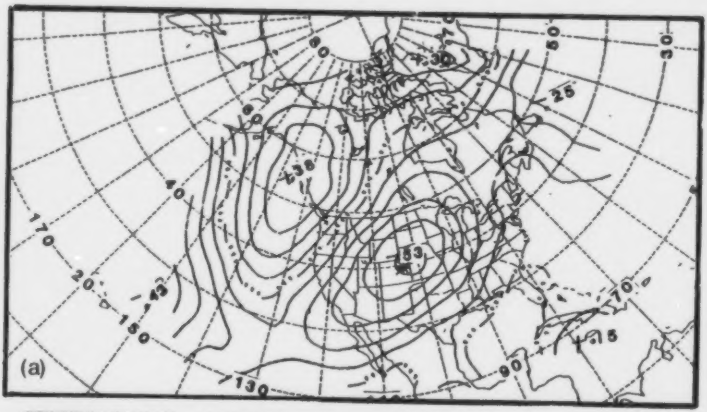

80
70
50
30
60
40
170
20
150
130
110
90
70
50
21
21
12

CENTRAL PLAINS CORRELATION * STD. DEV.

PRECIP. PERCENTILES. VS 700-MB. HT.

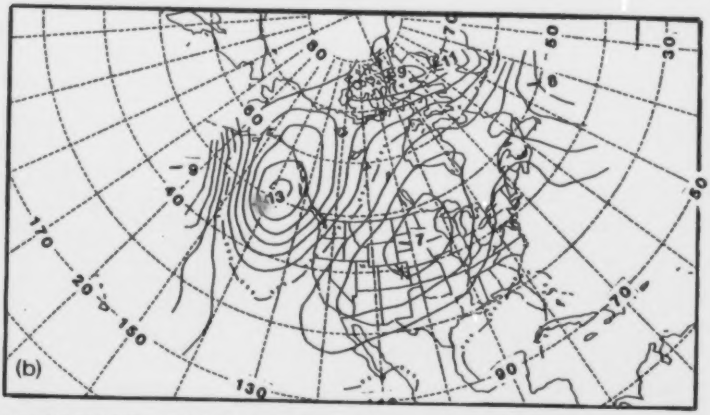
WINTER MONTHS 1951 - 1980

Fig. 21. Height anomaly map corresponding to precipitation in region centred at star. Isoline interval is 5 meters with zero line dashed.


(a)
80
60
40
170
20
150
130
90
70
50
30
.38
.53
.30
.25
-.43
.15

CENTRAL PLAINS CORRELATIONS SUMMER MONTHS 1951 - 1980

PRECIP. PERCENTILES. VS 700-MB. HT.

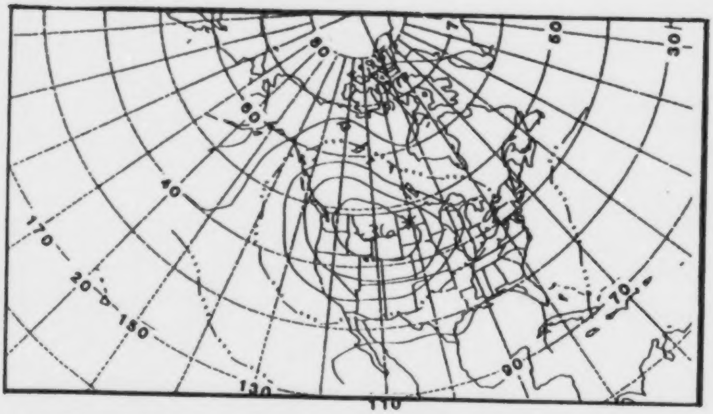

(b)
80
60
40
170
20
150
130
90
70
50
30
-9
13
7
9
11
6

CENTRAL PLAINS CORRELATION*STD.DEV. SUMMER MONTHS 1951 - 1980

PRECIP. PERCENTILES. VS 700-MB. HT.

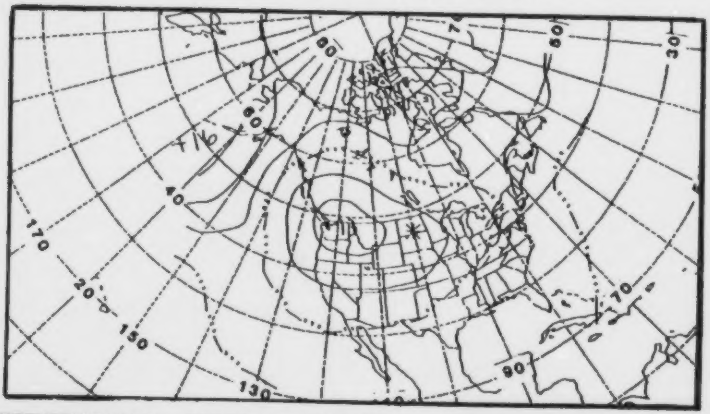
Fig. 22.(a) Field of correlation coefficients between monthly precipitation (summer) in region centred at star and concurrent 700 mb height anomalies. Isolines are drawn at intervals of 0.1 with zero line dashed.

(b) Height anomaly map corresponding to precipitation (summer) in region centred at star. Isoline interval is 2 meters with zero line dashed.


80
60
40
170
20
150
130
110
90
70
50
30
0

NORTHERN PLAINS CORRELATIONS WINTER MONTHS 1951 - 1980

PRECIP. PERCENTILES. VS 700-MB. HT.

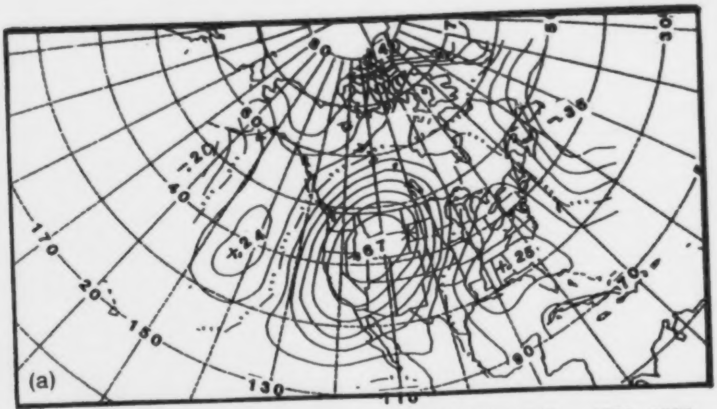

80
60
40
170
20
150
130
90
70
50
30
0

NORTHERN PLAINS CORRELATION*STD.DEV. WINTER MONTHS 1951 - 1980

PRECIP. PERCENTILES. VS 700-MB. HT.

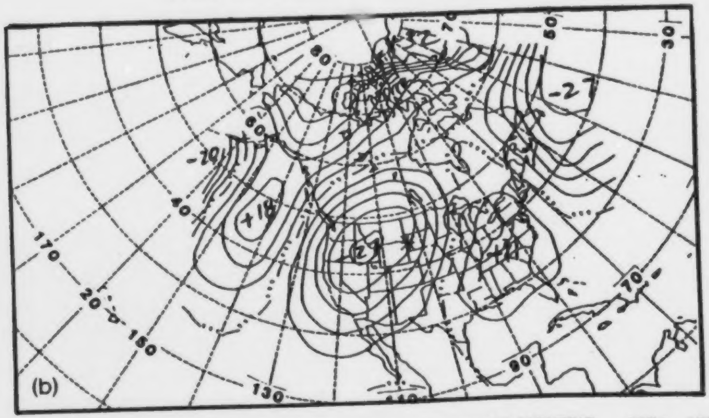
Fig. 23.(a) Field of correlation coefficients between monthly precipitation in region centred at star and concurrent 700 mb height anomalies. Isolines are drawn at intervals of 0.1 with zero line dashed.

(b) Height anomaly map corresponding to precipitation in region centred at star. Isoline interval is 5 meters with zero line dashed.


(a)
80
60
40
170
20
150
130
110
90
70
30
-.20
+.24
.67
+.26
-.36

NORTHERN PLAINS CORRELATIONS SUMMER MONTHS 1951 - 1980

PRECIP. PERCENTILES. VS 700-MB. HT.


(b)
80
60
40
170
20
150
130
110
90
70
50
30
-10
+18
21
-27

NORTHERN PLAINS CORRELATION*STD.DEV. SUMMER MONTHS 1951 - 1980

PRECIP. PERCENTILES. VS 700-MB. HT.

Fig. 24.(a) Field of correlation coefficients between monthly precipitation (summer) in region centred at star and concurrent 700 mb height anomalies. Isolines are drawn at intervals of 0.1 with zero line dashed.

(b) Height anomaly map corresponding to precipitation (summer) in region centred at star. Isoline interval is 2 meters with zero line dashed.

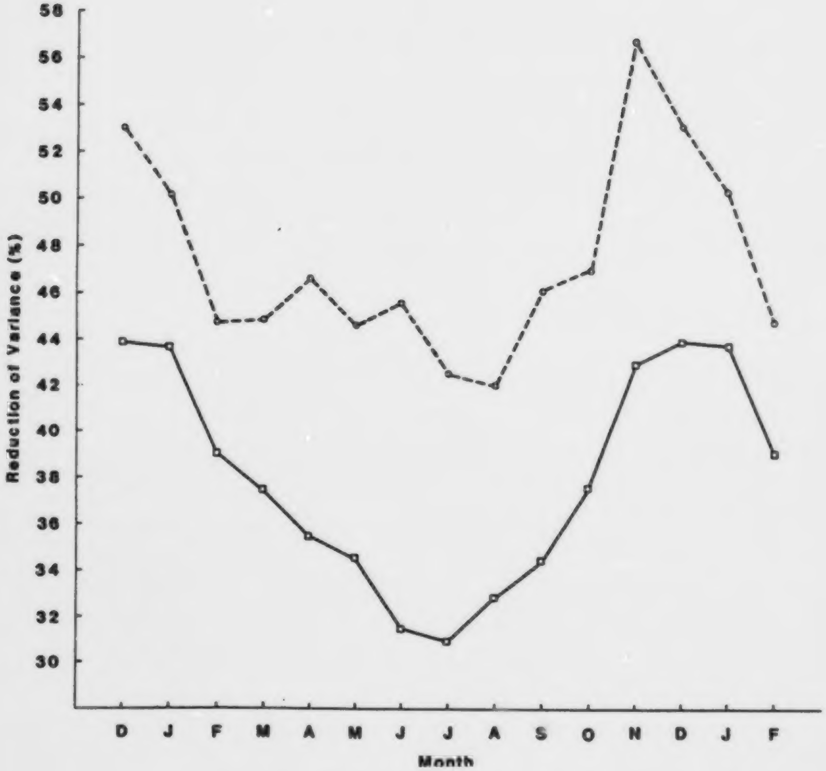


Fig. 25. Percent of monthly precipitation variance explained by specification equations averaged over 12 coherent regions (dashed) or 60 climate divisions (solid).

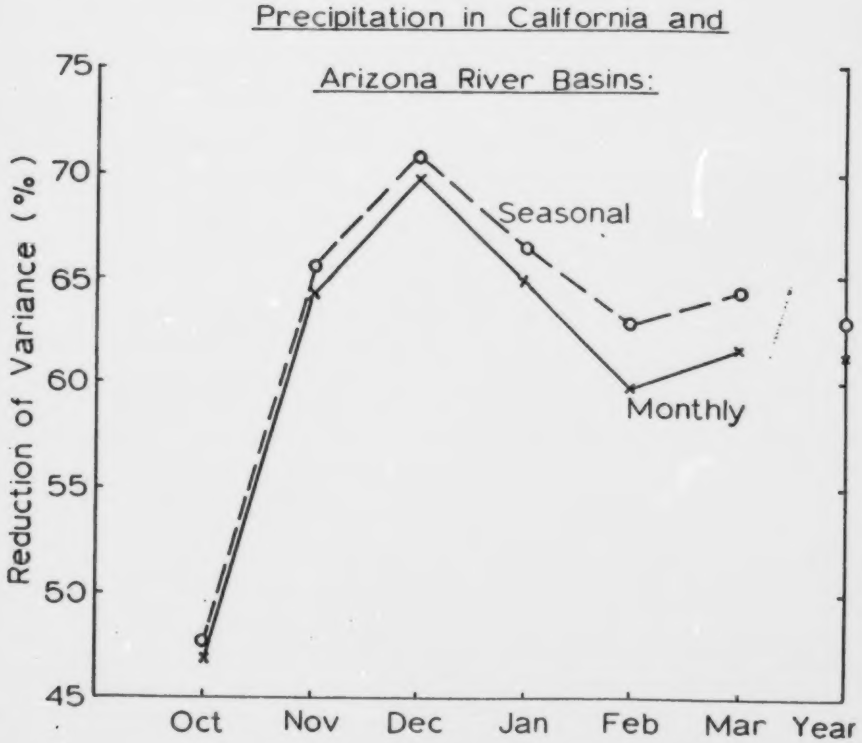


Fig. 26. Percent of precipitation variance explained by specification equations at four river basins in California and Arizona for seasons (dashed) and months (solid).

The Future of Drought Prediction on the Prairies

by

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Saskatoon, SK S7N 0W0

Why?

The ultimate aim in forecasting drought is to provide society with a warning in time for some mitigating action to be taken. This requires that possibilities for responsive actions exist, and that plans for implementing these actions be in place before the need to use them arises.

Droughts vary in their magnitude, frequency and duration of occurrence, as well as in their spatial characteristics. They have their earliest effects on soil moisture and vegetative cover, resulting in crop losses and wind erosion. Next to be affected are stream flows and lake levels, resulting in reduced availability of water for recreation, irrigation and hydroelectric power generation. If a drought continues, ground water supplies may be diminished, and even species composition of natural lands affected. Ultimately, the effects of the drought permeate all parts of the biosphere and the socio-economic system.

The drought of the 1930s struck the Prairies after the experience of a relatively wet period in the 1920s. The disastrous impacts of the sequence of dry years in the 30s were exacerbated because many of those farming at the time had little idea how to deal with them. During the ensuing years, with the help of the Prairie Farm Rehabilitation Act, the establishment of many dryland management practices has considerably reduced the sensitivity of Prairie agriculture to drought. Although the threat has been lessened, it has not been removed. Recent studies by Warrick (1984), Arthur and Kraft (1986), and Williams et al. (1987) found that in spite of technological improvements the agricultural system would still suffer great losses if the 1930's drought were repeated.

In most parts of the world, agricultural operations are still largely dependent on rainfall and suffer severely when it fails to arrive. Not long after the agricultural system feels the first effects of a drought, water supplies begin to be affected. The modelling approach is being used increasingly to predict the impacts of climatic variations, such as drought, on agricultural and hydrological systems. The main problems associated with such exercises are the proper integration of the component sub-models, such as those dealing with climate, crop-growth and economics.

Although Prairie society has "generally adjusted to withstand the normal range of fluctuations.....serious losses can and have resulted during prolonged dry spells" (Davis, 1984). A mild, dry winter in 1976-77 led to severe water-supply problems over much of the Prairies the following summer. This had major impacts on water supplies for irrigation, power generation and domestic uses. Subsequent droughts in 1980 and 1981 caused water tables to drop low enough to affect shallow farm and community wells, as well as ferry transportation on some Prairie rivers.

The Prairie drought of 1984-85 came on the heels of dry conditions the previous year. It affected agricultural production over most of the southern Prairies, and resulted in an estimated loss of over a billion dollars in Gross Domestic Product (Fautley et al., 1986). The effects were aggravated by low crop prices and high input prices and led to reductions in farm implement sales and construction starts, political controversy, and general pessimism (O'Brien, 1986).

Gilman (1985) has stressed the need for economic work to be done as a background to the use of a climate forecast. What is required is to determine what systems are likely to be affected , what the climatic effects on those systems will be, and what strategies are available to deal with them. If that work is not done, there is little likelihood of the subscriber getting a useful result out of the forecast. A study of the 1974 Prairie drought by Glantz (1979), posed the question "what would the impacts of the drought have been if agricultural decision makers had been warned about it the preceding autumn?". While some respondents believed that such a forecast might have brought them benefits, others considered that they had no choice other than doing what they had done anyway. The study indicated that the production of even a highly-skillful drought forecast may not, by itself, lead to socio-economic benefits.

An adequate drought policy and proper planning decisions can certainly help reduce the negative effects of drought, as can timely government response to drought situations. However, what happens when government advice is incorrect? A study by Glantz (1982) addressed the possible liability of an agency for issuing an incorrect forecast of drought. The U.S. Bureau of Reclamation predicted a shortage of irrigation water for the Yakima Valley of Washington, and instituted a rationing program. The prediction proved to be erroneous, and many farmers took legal action against the Bureau to recover losses. The study "raises the issue of who, if anyone, should bear the responsibility for the societal implications of such forecasts" (Glantz, 1982).

One common characteristic of droughts is the difficulty of recognizing them before they are well advanced. Once a drought is recognized, however, the important question becomes "When will it end?". Predicting the end of a drought is probably no easier, or more difficult, than predicting the beginning, and similar forecasting methods can be used. Karl et. al. (1987) described an approach to specifying the climatological probability of drought termination, using the Palmer Drought Index (PDI). Its usefulness as an aid in drought mitigation activities was demonstrated by applying it to the continental U.S.

On a more positive note, we should consider what can be done to ameliorate, or mitigate, a drought while it is occurring. It is possible that a number of mitigation measures would likely be of value. These include: greater use of snow management practices, improved irrigation management, selection of crop cultivars for drought tolerance, development of tillage practices for soil water conservation and greater use of windbreaks. With reference to the Canadian Prairies, McKay (1980) recommended that more effective use be made of meteorological information by analyzing statistically the meteorological characteristics of historical droughts and their social, economic and environmental consequences. This knowledge should then be exploited for the enhancement of the mitigation measures mentioned above and for the development of strategic and tactical plans for drought mitigation.

Another potential drought mitigation weapon is cloud seeding. Although not yet very successful at enhancing precipitation from mid-latitude convective clouds, it is possible that the method will become more effective in the future. A important question regarding its use to mitigate drought is whether there is a greater or lesser chance of success during drought compared with non-drought periods. Flynn and Griffiths (1980) analyzed rainfall during severe drought and non-drought periods in Texas. They found that severe droughts were characterized by both fewer and less intense rain events than normal. Although that meant fewer potential seeding days, there nevertheless was a possibility of limited success on those days. Data supplied by Isaac (1987) indicates that for some drought periods (on the Canadian Prairies), suitable clouds for seeding can exist in amounts comparable to the 30-year average amount. Thus the outlook for cloud-seeding during drought periods may not be as gloomy as conventional wisdom might indicate. An aspect that merits further investigation concerns the availability of naturally-occurring freezing nuclei during periods of drought. Many of these nuclei are produced by decomposition of plant material and are carried into the atmosphere by convection currents. While total suspended particle amounts may not be significantly different from normal during some drought periods (LaDochy and Annett, 1982), it is possible that the freezing nuclei proportion may differ.

Parry and Carter (1987) concluded that although the "connections between a climatic event, its biophysical effects, the economic costs of prevention or compensation, and the social impacts of all of these are imperfectly understood", there has been "some degree of success in simulating these connections with a hierarchy of models of varying degrees of complexity". This feeling was echoed by Lamb (1987), who suggested that "a truly inter-disciplinary, as opposed to multi-disciplinary, effort will thus be required".

How?

At the present time, there is no completely satisfactory method that can be used routinely to predict mid-latitude climate over the month-to-season time range. A recent study (Ripley, 1988), however, indicated that the potential for improvement exists, and that there is reason to expect better forecasts within the next decade if research effort in this area continues.

The predictability of present numerical methods is limited to a week or so, and this is unlikely to be extended in the foreseeable future beyond a month. While forecasts for such short periods have little significance for the outbreak of drought, they may be extremely valuable with respect to its termination. The main hope for improvement in monthly-to-seasonal forecasts appears to rest on the realistic simulation of the surface boundary conditions, namely of: soil moisture and vegetation, snow cover, and the state of the oceanic surface layer including sea ice and sea-surface temperatures. Major factors in the improvement of longer-scale numerical predictions will be the coupling of atmospheric and oceanic global climate models (GCMs), the provision of a more realistic treatment of land-surface processes, and the use of more-sophisticated averaging methods to remove the high-frequency transients from model output.

Many empirical forecasting methods now show some long-range skill for temperature, but not for precipitation. Nevertheless, the field is advancing rapidly and great strides have been made in short-term climate prediction (STCP) for the tropics and many sub-tropical areas, such as the Sahel (Folland et al., 1987), India (Shukla and Paolino, 1983), northeast Brazil (Hastenrath, 1986), and Australasia (Nicholls, 1982).

A higher level of "weather-noise" makes the mid-latitudes more difficult to deal with, but this problem may not be insurmountable. Diagnostic studies are revealing many weather patterns that are teleconnected to surface anomalies such as the El Niño/Southern Oscillation (ENSO). A significant characteristic of these anomalies is their persistence, making them potentially valuable predictors for long-range forecasting. However, there is increasing evidence that predictability will vary with location, with season, and with synoptic situation. One important research area will have to be this determination of potential predictability, so that effort will not be wasted trying to do the impossible. This will require extending the work of Chervin (1986), and investigating new ideas such as the climatic attractor approach suggested by Fraedrich (1987).

It is conceivable that some parameters or indices may be more predictable than others. For example, the nature of the processes involved make precipitation a far more difficult parameter to forecast, and verify, than temperature. The existence of a negative correlation between temperature and precipitation, in many drought-prone areas, may make it easier to predict a drought index, such as the PDI or the crop moisture index (CMI), than precipitation alone. However, a study of the spatial characteristics of drought duration in the United States, by Karl (1983), found that although the PDI showed considerable skill as a contingency-table predictor up to 12-months ahead, forecasts using it were not significantly better than those obtained using precipitation itself.

The usual practice of forecasting time-averages instead of instantaneous values, in STCP, has been questioned by Van den Dool (1985). Not only are time-averages much less useful, but such forecasting obscures the distribution of skill through the period. Since most of the skill in longer-range forecasts is to be found in the early part of the period, an extension of the forecast period tends to dilute the skill. He concludes that the only justification for forecasting monthly or seasonal averages is to facilitate statistical skill testing.

A similar concern relates to the forecasting of extreme cases, such as heavy rains and prolonged droughts. There is some evidence that extreme events "cast their shadows well before they take place" (Namias, 1985), and hence may be more predictable than less extreme events. There is no question that weather extremes have greater impacts on society, and that their prediction is more desirable. They may, however, be even less predictable (Gilman, 1985) because less is known about their statistics, and because of a greater stochastic element in their occurrence. These two views need to be examined and reconciled in the case of Prairie droughts.

According to Pearce (1985) "Future progress in medium and longer term prediction will depend crucially on progress in understanding the dynamical and physical processes involved on these time scales....This is likely to be achieved primarily through experimentation with numerical models linked with sophisticated diagnostic studies of observational data on the global scale". This sentiment is reinforced by Preisendorfer and Mobley (1984), who "hope that future research will lead to hybrid dynamical-statistical-analog methods which will indeed be of significant importance".

Thus, numerical models are likely to play an increasing role in producing the early part of a monthly forecast, supplemented by empirical methodology beyond that. Because of this, monthly and seasonal STCP may well diverge during the next decade (Rasmusson, 1987), with dynamical methodology becoming increasingly used in monthly predictions. Seasonal forecasting, on the other hand, will likely continue to be dominated by empirical methods, but with inroads by coupled ocean-atmosphere-land surface dynamical models. Numerical modelling will also be able to provide a measure of the degree of probability or confidence to be associated with the forecast. If dynamical models are to become capable of predicting on the monthly-to-seasonal time-scale, they will have to be able to simulate faithfully the life-cycles of individual synoptic systems and their feedbacks, while simpler models must include parameterizations of transient-flux convergences to reproduce these feedbacks (Hoskins and Sardeshmukh, 1987).

Cautionary Note.

The complexity of the global climate system cannot be overstated. The more closely it is examined, the more detail it reveals. We are never likely to achieve an understanding of the system sufficient to enable us to produce a method of climate prediction that will be as accurate as most of us would like. Some of the difficulties that are involved will perhaps be illustrated by the following example.

As indicated above, ENSO produces very strong signals in some tropical and sub-tropical regions. Weaker signals have been noted as well in many extra-tropical areas, such as western Canada. The mild, dry winters of 1986-87 and 1987-88 have been attributed by some to ENSO. If this is so, one might ask if previous ENSO events produced mild, dry winters as well. Figure 1 is a plot of an indicator of ENSO, the Southern Oscillation Index (SOI), during the past 13 years, extracted from the Japan Meteorological Agency's Monthly Report on the Climate System for November 1988. It shows an anti-El Niño event in 1975/early 1976 (positive SOI), and major El Niños (negative SOI) in 1977/78, 1982/83, and 1987/88.

One may then ask whether the climate at a particular point on the Prairies (such as Saskatoon) was affected by these occurrences. This, of course, neglects any spatial patterns of anomalies that are usually present. One may attempt to justify this neglect on the basis of the strength and great spatial extent of the ENSO forcing mechanism. Figures 2a and b show the anomalies (from normal) in monthly temperature and precipitation values at Saskatoon during each of the four above periods. The 1975/76 cold event was accompanied by a generally cold first winter but warm second winter. The first warm event exhibited the reverse characteristic, while the second was more similar to the cold event, and the third was characterized by above-normal temperatures both winters. The precipitation patterns were just as varied--the cold event exhibited relatively small variations about a near-normal average, while the warm events varied from a considerable increase in the 1982/83 case to a very large deficit in 1987/88. The 1977/78 warm event averaged somewhat below normal, although May 1977 was the wettest on record!

Thus while there appear to be some relationships between temperature and precipitation anomalies and ENSO events, they obviously do not tell the whole story, and other factors must also be involved.

Recommended Research.

The following recommendations for research that is likely to lead to improved drought prediction, on the Canadian Prairies, in the one to three month range were extracted from Ripley (1988).

Major Research Areas

1. The spatial and temporal patterns of drought occurrence on the Prairies, particularly the delineation of coherent regions, should be established. More information is needed regarding the timing, duration, intensity, spatial extent, and predictability of Prairie droughts.

2. These drought patterns need to be related to synoptic situations or map-types, and in particular to up-stream and down-stream teleconnections. Relationships can then be sought between the synoptic patterns and forcing functions such as ENSO. A prime example is the PNA pattern, which is known to be associated with both ENSO and anomalous weather over western North America.

3. The associations between these synoptic situations and surface-boundary forcings such as ENSO need to be investigated. Although an ENSO signal has been recognized in the winter-time temperature field in western Canada, none has been found in the precipitation field, or in other seasons. Further investigations should be carried out, looking at cold as well as warm ENSO events. Even if the signal is present only during the winter, there may well be some carry over into the following spring and summer through soil temperature and snow cover effects.

   ENSO effects are likely to be greater over the Rocky Mountains than farther east (Cayan, 1987). This region merits study since it is the source of much of the early-summer stream flow in the Prairies.

   The effects of other local and remote surface anomalies should be investigated, using both studies of historical data sets and numerical simulations. The most promising are likely to be North Pacific Ocean SSTs, Arctic sea-ice extent, and North American snow cover and soil moisture. Several new data sets have recently become available that will assist in this. There is a major need for improving the modelling of land-surface processes to facilitate the numerical simulation side of this work.

Minor Research Areas

1. Investigate whether droughts which are extreme, in terms of intensity, area affected, or duration, are more or less predictable than less-extreme droughts.

2. Investigate sunspot/QBO relationships with Prairie droughts, in light of the recently-discovered relationship between the QBO and the solar cycle.

3. Investigate the simplified-dynamics modelling approach to monthly and seasonal climate prediction on the Prairies.

4. Investigate potential relationships between the latitudinal distribution of atmospheric aerosols and weather patterns over the Prairies.

5. Investigate the optimum format and delivery method for supplying the drought forecast to potential users (see Appendix A). User acceptance, comprehension and confidence should all be considered.

6. Investigate the use of indicators other than precipitation and temperature quantiles for use in drought forecasting. The various existing drought indices, such as the PDI and CMI, need further assessment and, perhaps, modification. Use of other aspects of precipitation (such as rain days, dry days and rainfall intensity) should also be considered.

7. Investigate temporal patterns in drought occurrence using a chaos-theory approach.

The above research should be conducted with as much co-operation and support of the potential users as possible. This will not only ensure that the research stays "on track", with respect to their needs, but also will help to build up credibility in the procedure by keeping them informed and involved as the work progresses.

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Appendix A

Survey of Potential Forecast Users (Ripley, 1988).

1. Almost all of those contacted were interested, and felt that such forecasts would be useful to them.

2. Precipitation was the preferred forecast parameter, followed by temperature, evapotranspiration, wind, sunshine, and drought indices.

3. Potential uses included:
   --to provide lead time for the introduction of impact reduction measures.
   --to provide lead time for advising, warning, and educating their constituents.
   --to provide input for computer models of hydrological basins, soil moisture, etc.
   --to aid in planning for new developments.
   --to aid in budgeting for drought-related expenses.

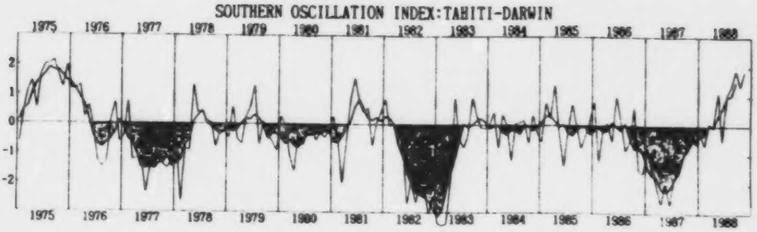


Figure 1 -- Variation of the Southern Oscillation Index during the past 13 years. Negative values indicate a warm (El Nino) event, and postive values a cold (La Nina) event. (from Japan Meteorological Agency, Monthly Report on Climate System).

Figure 2a -- Saskatoon Temperature Anomalies During ENSO Years

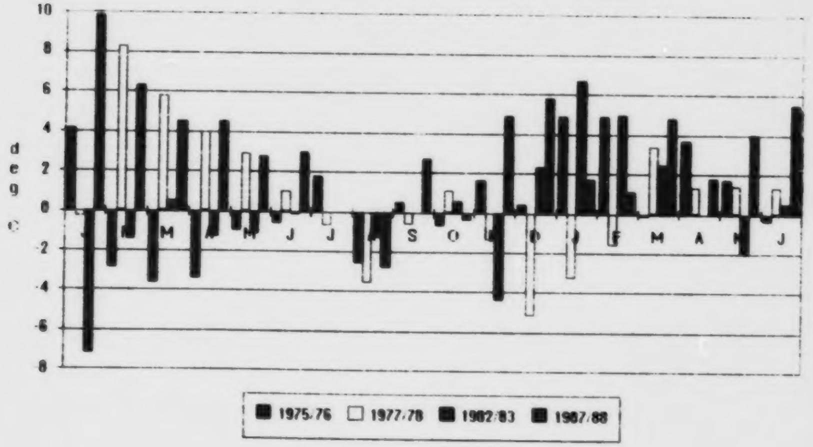
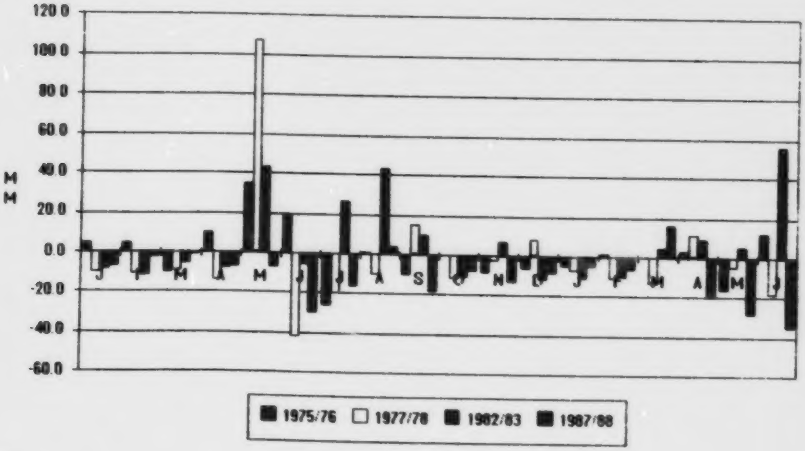


Figure 2b -- Saskatoon Precipitation Anomalies During ENSO Years



Session 3 - Working Group Questions and Issues

General

Working Groups can choose to address one or two of the following questions and issues, or adapt them, or devise their own questions.

3.1 Prediction Verification

Should drought predictions by various forecasters be compared in some standard fashion with observations, in order to provide verification of claimed or assumed accuracy? How might this be done conceptually and what organization(s) might be able to do it? This problem may assume increasing importance to users as more forecasters, including private concerns, enter the field of drought prediction.

3.2 Predictability

Is the atmosphere predictable over the 1-3 month time scale? How might this compare to the predictability for even longer periods, considering trends and cycles which may be present?

3.3 Accuracy Requirements

What degree of improvement of accuracy over a climatological forecast is necessary for a drought forecast to be useful to various agencies or to the "public"? How must drought forecasts be promulgated in order to be useful (i.e. would a text with qualifying phrases be acceptable if that were all that was achievable, or is quantification essential)? How geographically specific must drought forecasts be in order to be useful?

3.4 General Circulation Models

What role can general circulation numerical models, including atmosphere/ocean coupled models, play in drought prediction? Are the techniques for relating these model outputs to monthly surface temperatures and precipitation adequate?

3.5 Teleconnections

Is the research on teleconnections, seas surface temperatures (SSTs), and drought worth pursuing in the context of drought prediction? If so, how might it be incorporated into

DROUGHT PREDICTION

Summary

Peter R. Scholefield - Session Chairman

Notes from the Working Groups

It is important to note that the working groups recognized that there is no existing capability to predict droughts, so the group discussions centered around topics related to the long-range forecasting of the important meteorological parameters of precipitation and temperature. After having spent some time with each group during their discussions and then subsequently being debriefed by the working group chairmen, I found that there seemed to be agreement among some of the groups on certain points which are summarized according to the five specific questions asked (attached) as follows:

Prediction Verification

The need for verification through user feedback was expressed as well more communication (particularly by AES) of verification results to the user, including comparative statistics for similar products produced by different organizations. Forecasts and verification should be continued routinely to give the user a feel for the utility of the products.

Predictability

It was generally felt that there was some reasonable degree of predictabilty of anomalies over a one-month period, especially for temperature. Hope was expressed that useful anomaly forecasts for longer periods up to three months can be developed but would have to be based on forecasting upper-level flow patterns through better understanding of teleconnection relationships and surface forcing mechanisms such as the ENSO.

Accuracy

There were some questions as to the utility of existing long-range forecasts that show some skill. Marginal improvements in skill would be welcomed but forecasts may still not be useful until there is a significant improvement in accuracy. A measure of the forecaster's confidence would improve the utility of forecasts. A common desire was expressed for more detail in forecasts with regard to magnitudes of anomalies, temporal evolution and geographic resolution.

General Circulation Models

There was some confusion between the differences between the application of GCM and NWP models to the long-range forecast problem. It was felt that NWP models show promise to improve the accuracy of forecasts out to one month while GCM simulations can help improve our understanding of the climate system which will be required to develop improved long-range forecasts. Continued research using models was recommended.

Teleconnections

Despite some skepticism, it was generally felt that the empirical/teleconnection approach is worth pursuing to help identify factors related to drought and give some direction to physical modelers. It is important to try and understand the physical basis for teleconnections and to consider hydrologic as well as atmospheric parameters.

Recommendations

The following recommendations were based on discussions and notes from the the seven individual working groups and on information from the addresses of the two keynote speakers, Professors V. Yevjevich and W.H. Klein and the invited speaker, Professor E. Ripley:

The Atmospheric Environment Service should take the lead in educating users and potential users of long-range atmospheric forecast products by:

a. documenting all scientifically reputable medium-range (5-15 days) and long-range (16-90 days) forecast products available to Canadians and describing for each one:
  - its availability;
  - methodologies used in preparation;
  - accuracy including comparative verification statistics for similar products; and
  - how to best interpret and utilize each product with particular reference to drought forecasting.

b. cautioning users against the use of scientifically-unfounded long-range forecast products.

c. discussing the potential for future improvements in the field of long-range weather and climate forecasting.

There should be continued research into developing the physical/dynamical model approach to long-range forecasting which will require increased computer power to realize the potential of the forecast models.

More effort should be devoted to developing statistical/empirical approaches to long-range forecasting with specific emphasis on the following drought-related initiatives:

- further studies to delineate the spatial and temporal patterns of drought occurrence, as well as its predictability;
- establish relationships between these patterns and their corresponding synoptic situations; and
- investigate associations between these patterns (and their corresponding synoptic situations), and potential surface forcings such as ENSO and anomalies of North Pacific SSTs, Arctic sea-ice extent, and continental snow cover and soil moisture.

SESSION 4

DROUGHT IN THE FUTURE

Future Drought on the Prairies

F. Kenneth Hare, Chairman
Climate Programme Planning Board

(Address delivered to Prairie Drought Symposium, Saskatoon, Oct. 13, 1988)

Introduction

There is widespread speculation that major climatic change lies before us in the next few decades, and that western North America may be a chief target of such change. This view arises from scientific modelling of the greenhouse effect, the supposed impact of rising concentrations in the atmosphere of carbon dioxide and other gases capable of absorbing infrared radiation. A warming of several degrees Celsius in mean annual temperature is foreseen. Associated with this warming may come a northward shift in precipitation belts, and a general increase in growing season evaporation. Some models predict a large decrease in summer soil water availability in the great Plains-Prairies region of North America.

It will be my argument today: (1) that this threat is still poorly focused, and has a large measure of uncertainty attached to it; (2) that the hypothesis is nevertheless plausible; and (3) that planning for future water resource management and agricultural practices should attempt to improve the Prairie economy's ability to cope with increased drought, higher temperatures and altered seasonality.

These ideas as to the regional future need to be assessed, however, on a wider platform. If the greenhouse effect is real, and if we have correctly diagnosed its present and future impacts, there will be consequences for the entire world. The recent World Conference on the Changing Atmosphere: Implications for Global Security (Toronto, June 27-30th, 1988) took a dramatic view of the implications. "Humanity is conducting", said the Conference Statement, "an unintended, uncontrolled, globally pervasive experiment whose ultimate consequences could be second only to a global nuclear war". This dire process will arise from "pollutants arising from human activities, inefficient and wasteful fossil fuel use and the effects of rapid populations growth in many regions". The presence of Prime Ministers G.H. Brundtland of Norway and Brian Mulroney of Canada, and the chairmanship of Ambassador S. Lewis, gave added visibility to the Statement's content (AES, 1988).

It will not be lost on this audience that Canada's customers for export wheat, coarse grains and animal products may be as much affected as Canada itself. If the threat is real, there will not only be a direct impact on Prairie farmers, there will also be external changes in markets. And if the strong language of the Toronto Conference Statement is justified, the farm economy of western Canada, already in delicate health, may have to face further disruption. So will the water supply system, so crucial to everyone. This is not a worry for farmers alone.

These ideas are by no means new. They have been widely aired at similar conferences for much of the past decade (e.g., Hare, 1981; McKay, 1986). The implications for the Prairie economy have been examined with some care (e.g., Kraft, 1984), and the direct impact on Saskatchewan farm practice has been analysed in relation to the predictions of specific climatic scenarios (Williams, Fautley, Jones, Stewart & Wheaton, 1988). But little attention was given nationally to earlier predictions. The Toronto Conference Statement, and a general rise of public anxiety about environmental issues, have altered matters. The greenhouse effect is now widely understood and feared by the public and its commentators. Hence the moment is ripe for a re-examination here in Saskatoon.

What will be the direct impact of a greenhouse warming?

Theory predicts that rising concentrations of the greenhouse gases (carbon dioxide, nitrous oxide, methane and various pollutants, notably the chlorofluoromethanes), coupled with feedback mechanisms involving water vapour, sea ice and snow-cover, should raise temperatures at the earth's surface. For a doubling of the combined effect of all the gases, possible by the year 2030, a rise in average surface air temperatures in the range of 1.5°C to 4.5°C has been predicted (Villach, 1985). This prediction rests on elaborate modelling of the general circulation of air and sea on a global scale (see Dickinson, 1982, for a general review).

Unfortunately the models used in these predictions differ among themselves as to details, and generally do a poor job of predicting regional patterns. They achieve moderate agreement as to global impacts, but differ alarmingly on the geographical scales important to economic decision making (Grotch, 1988). This is especially true as to precipitation, the element of most interest to the Prairie Drought Workshop. To summarize:

(i) general circulation models available at present, (e.g., Hansen et al., 1983, 1984 - the GISS models Manabe and Stouffer, 1980; Manabe and Wetherald, 1986) predict a rise in temperatures in the Prairie region of 3 to 9°C in winter temperatures, and slightly smaller values in summer;

(ii) the models that specifically predict precipitation (e.g., GISS) imply increases over the Prairie region, but also greatly increased evapotranspiration. The latter outweighs the effect of increased precipitation (Williams et al., 1988). The net effect, if high interannual variability continues should be an increase in the frequency of droughts, and considerable economic losses.

Can we trust such estimates? Only in a qualitative sense. For Regina, for example, the GISS model widely used in impact analysis, when applied to present conditions as to greenhouse gases, predicts a much milder winter and a cooler summer than is actually observed (Williams et al., 1988, especially Figures 1.9 - 1.10). The consequences of doubled greenhouse warming can be deduced by a comparison of model results using present greenhouse conditions with those using doubled conditions. These differences in temperature (or ratios in precipitation) can then be applied to present day real conditions, though the justification for such a procedure is dubious. Moreover, the handful of models available differ so much among themselves that little confidence can be attached to such quantitative estimates (Grotch, 1988).

But one must start somewhere, and it is better to start with model predictions than with wild guesses. Some years ago the Canadian Climate Centre, with the support of my Board, suggested the use of GFDL (Manabe and Stouffer, 1980, updated to 1984) and GISS scenarios for doubled greenhouse effect analyses. The Williams et al., 1988 studies discussed above, and the work of Cohen (1986) and Cohen and Allsop (1988) on the Great Lakes, followed this advice. In my view the procedure is fully justified. It can be adapted as better model estimates become available. Meanwhile I accept the assessment of one recent user of the regional detail of the GISS scenario: "the results have demonstrated that it is possible to make useful translations of climatic scenarios into estimates of likely effects on agricultural production, on the environment, and on the economy" (Williams et al., 1988, page 226). The operative word is "useful" - but not necessarily convincing.

I doubt if even this lukewarm optimism is justified in relation to hydrological predictions. The GCM's fail to predict meaningful detail on the precipitation map, and do so for a fundamental reason: that the grid size filters out most of the sub-synoptic scale system. The mesoscale spectrum of organized weather systems is largely missed. Even on ordinary weather maps we still cannot adequately relate moving synoptic scale systems (cyclones and anti-cyclones) to mesoscale detail. Still less can we safely infer the statistics of mesoscale precipitation systems from GCM predictions in their present form.

In summary, the available models predict, with respect to doubled greenhouse warming:

- a substantial warming in all seasons, the models differing widely as to magnitude
- with a lower degree of confidence, especially as regards regional detail, increased precipitation in most months
- increased evaporation through the growing season on a scale outweighing precipitation increase; there will hence be less available soil moisture, and less local run-off (though there may be increased snow-melt from the Rockies)

There are many months in the recent climate record, and some entire seasons, that display anomalies in temperature and precipitation like those predicted by the models for a doubled greenhouse effect. 1982-83, the great el Nino year, produced such anomalies. So did the winters of 1986-1988. Possibly the great drought of 1988 is advance warning of future norms, though I emphasize the word "possibly"; other interpretations are much more likely.

Where does this leave us?

The professionals in this audience are mostly meteorologists, water engineers and hydrologists. Their jobs are to guarantee adequate water supply to Prairie farmers and cities. What do the above model predictions imply for their jobs?

First, and quite immediate, is the question they all have to answer, which is simply "is the greenhouse effect real?" And immediately afterwards, "what do we do about it?"

All I can say in relation to the first of these questions is that theory, represented by the models, fits the observed facts, represented by the climatological record, at least as far as temperature is concerned. About the second I can say

(i) very long-term precipitation records show little sign of real change. Behind large interannual variations the central tendency seems stable. The same is true of streamflow records of run-off. These generalizations are true of many regions of the earth, though not necessarily of individual drainage basins. I am not aware of evidence of systematic long-term change in streamflow in the Prairie rivers, though groundwater records may be less reassuring. I know of no confirmation of the view that evapotranspiration is increasing.

(ii) on the other hand there is clear evidence (Jones et al., 1986; Jones, 1988; Wigley, 1988, personal communication) that global mean air temperatures near the earth's surface have increased by about 0.5°C in the past century. This trend is nearly linear, when a careful job is done to weight the data so as to include land and sea observations. It is visible in both hemispheres. But in any one region, such as the Prairies, it is likely to be obscured by larger interannual or interdecadal fluctuations. The climatic record is very noisy and the signal of climatic change only emerges with difficulty. The observed warming of 0.5°C is within the range of estimates for the past century derived from models of greenhouse warming (Villach, 1985).

This concordance of theoretical estimates with observed warming led me to say cautiously (Hare, 1988a that it is time to take the greenhouse effect seriously, to assume that it will continue, and accelerate, and to begin planning measures of adaptation. I was promptly attacked by John Maddox in a leading article in Nature (Maddox, 1988), who said that I should know better. I replied (Hare, 1988b) that I did know better, since every objection he entered was well-known to specialists, and had been taken into account. But Maddox is correct in saying that the effect is as yet unproven. It is merely the most likely explanation of changes in progress, which will probably raise many problems for future water resource management in the Prairie Provinces.

Is surprise possible? We generally assume that the changes aforeseen will arrive slowly, probably showing themselves in an increasing frequency of warm, dry summers and mild winters, though high interannual variability will remain the dominating fact. The model predictions discussed above are for the most part equilibrium estimates, in which the model is first applied to existing conditions, and then repeated with doubled or quadrupled greenhouse effect. Hansen et al, (1988) have shown, however, that a modified form of the GISS model responds realistically (and gradually) to a slow build-up of the greenhouse gases, at least over the past two and a half decades. To a limited extent there is thus support for the view that the greenhouse warming will be fairly gradual in human economic terms - though still more rapid than anything known in the geological record. But a per saltem jump to a new equilibrium is not impossible. Such jumps have occurred in rainfall records from other regimes (for example, in East Africa in 1961, and Australia in 1973-74), though these turned out to be prolonged fluctuations rather than lasting changes. Theoretical analysis suggests that lasting jumps are possible, but observation confirms that they are very unlikely.

Since the 1981 Regina drought workshop, held in the midst of a drought (Hare, 1981; other articles in same report), there have been several droughts on the Prairies, 1988 offering one of the most severe case. These have kept public concern alive, and professional opinions apprehensive. There are no grounds for supposing that these droughts arose from the onset of a greenhouse warming. Nevertheless, they have provided a striking reminder that drought is a recurrent phenomenon, and that growing needs for water (which a warmer climate will guarantee) are unlikely to be helped by the greenhouse effect.

I conclude with a restatement of my opening remarks:

- that the greenhouse effect looks increasingly probable as the mechanism underlying the warming of the past century, and still in progress
- that if this diagnosis is correct, rising future concentrations of the greenhouse gases suggest that the warming will continue and intensity, lengthening the growing season and increasing irrigation demand
- that the effects on precipitation are obscure, because of the poor performance of the available models on the regional scale. Some models predict increases in precipitation, and even larger increases in evapotranspiration, leading to decreased soil moisture availability and run-off; and
- that planning for future water resource management should take these possibilities (now trending towards probabilities) into account.

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AVAILABLE CLIMATOLOGICAL DATA SETS FOR STUDYING DROUGHT

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This talk will deal primarily with a discussion of climatological data sets available and of some of the methodologies used for drought studies. The data sets to be discussed are those which are available from the Atmospheric Environment Service (AES) and can be easily provided on request.

Data Sets

In the study of droughts, we are interested in past and present climate data as well as possible future climate scenarios. Consequently, I will discuss the data sets in three groups (Figure 1).

1) **Proxy Data.** Prior to 1843, we must rely on proxy data to describe the past climate in Canada. Our oldest instrumented climate station is Toronto Bloor Street. Although it began temperature observations in 1839, it wasn't until 1843 that both temperature and precipitation were measured. At AES there has not been much work done on proxy data. Proxy data studies in which AES was involved have been through contracts or support of visiting scientists. The most recent work was done by Joel Guiot (1986) who was a Post Doctoral Fellow in the Canadian Climate Centre at the time. His area of study was around the Hudson Bay and the Canadian Shield. Figure 2 shows some of his reconstructed temperature time series for selected stations from 1700. I must confess that I know very little about the methodologies used in the analysis of proxy data and have always found the results to be somewhat mystical--that whole field to me may be described as "voodoo" climatology. This is not to be taken in a derogatory sense, in fact, I have great respect for those scientist who can take tree rings, ice cores, pollen grains, shells and mud samples and produce some very interesting and useful climatic time series. In spite of Professor Yevjevich's caution on the interpretation of these time series, they are still the best we have with respect to looking into past when instrumented records were not available.

2) **Instrument recorded data.** As mentioned earlier, our oldest climate station with instrument recorded temperature and precipitation is Toronto Bloor Street which began these observations in 1843. There are two data sets based on instrument observations which are useful for drought studies. One data set is the actual data recorded at each station. Table 1. If we consider only daily temperature and precipitation as basic climate parameters, there are approximately 575 Canadian

stations with 50 or more years of data. For stations with 100 or more years of data, the number drops to only 56, thus we do not have a large station set for long time series studies. Our archive system, however, has improved considerably in recent years and we can provide these data on an easily accessible format on both standard 9 track magnetic or on MSDOS format floppy diskettes. The contact for these data is Mike Webb in the CCC. The spatial distribution of these long term stations is shown in figure 3(a). As expected, the greatest concentration of stations is near the Canadian-U.S. border. Figure 3(b) shows a typical application of station data which in this case is a monthly Palmer Drought Index time series for Regina. Regina is one of the oldest climate stations in Saskatchewan with 105 years of record.

The second data set based on instrument observations is a gridded data set. Table 2. This data set was recently developed to improve on the spatial distribution of the actual climate stations and for use in the comparison and evaluation of general circulation model (GCM) outputs. This gridded data covers the Canadian land portion between 40° to 90° N latitude and 50° to 150° W longitude. The gridding scheme chosen uses a latitude-longitude tag. South of 70° N latitude the grid spacing is 2° latitude by 4° longitude. Because of the convergence of the longitude lines north of 70°, the longitude grid spacing is doubled to 8°. The approximate size of the resulting grid square at 50° N latitude is 280 km by 230 km and at the higher latitudes it is 320 km by 230 km which are comparable to the grid size of most GCMs. The total number of grid points in this data set is 256 and the available parameters for each grid point include daily and monthly values for maximum, minimum and mean temperature and total precipitation for the period 1951 to 1980. This data set is also available on standard 9 track magnetic tape. Henry Hengeveld is the contact person in the CCC for this data set.

Figure 4 illustrates the grid over Canada. One of the objectives in developing this data set was to maintain the variability in the data so that extreme events are preserved. The method for interpolating from a station to a grid point was to use only the nearest station if it is within 100 km of the grid point rather than using a spatially averaged values which would have a filtering effect on the data variability. Where no stations are within 100 km of a grid point, data from the two nearest stations were used, but that was the maximum number of stations used to interpolate a grid point value.

3) **GCM outputs.** The last data sets to be discussed are the outputs from GCMs. We have compiled the outputs from 3 American models: the Goddard Institute of Space Studies (GISS), the Geophysical Fluid Dynamics Laboratory (GFDL), and the Oregon State University (OSU). There is a Canadian GCM developed by the Numerical Modelling Division in the CCC but increased

CO_2 scenario outputs from this model are not yet available. The spatial resolution for the different models are given in table 3. The OSU model actually has a finer resolution of 4° x 5° but the data that have been abstracted is 4° x 10°. I do not know the reason for this. The data set we have available was provided by NCAR and contains data from the 3 American model covering Canada.

These models are first run at the 1 x CO_2 level to equilibrium as the control run. The CO_2 content of the atmosphere is then doubled (in some of the models the other active gases are also increased) and the models are run to equilibrium to generate 2 x CO_2 scenarios. The monthly data from these model at their equilibrium state have been abstracted. The GISS model also has transient outputs which provide data each decade until equilibrium is reached. Unfortunately, we do not have these transient outputs. Table 4 lists the 7 parameters we have abstracted and compiled. There are many other parameters in the model outputs but these were the ones thought to be the most useful. These data are available on 9 track magnetic tape and MSDOS floppy diskette. The CCC contact for these data is Tom Agnew in the Climate Program Office.

Table 5 is an example of the data and its format. Shown is the GISS model output which has been windowed for the grid that covers Canada. The area which is enclosed includes the grid points which cover the 3 prairie provinces. The dot indicates approximately where Saskatoon is located. What is shown in this example is the difference between the control run and the 2 x CO_2 scenario for July monthly mean temperature. If we average all 12 grid points over the prairies, there is a 1.5° C increase for the 2 x CO_2 scenario. However, it is interesting to note that there is at least one grid square which shows a decrease in temperature.

Comments on current methods for studying future droughts

I would now like to make a few comments on some of the current methods which make use of these data sets in drought studies.

Some of the very early studies were essentially model sensitivity studies. A hydrological model was taken and run with one of its parameters, for example, the temperature time series increased by a factor, while the other parameters were held constant. Interpretation of the model output was then made for the increased temperature scenario. This method was simple and does not require much data. However, it does require a lot of faith in the model used since it must assume that the model can extrapolate results beyond it calibrated range.

Another method is in the other extreme in complexity. GCM models are used directly to examine the hydrological processes and in particularly drought events. The problems with this approach are the poor spatial resolution due the relatively large grid size (300 km x 300 km) of GCMs and the fact that the parameterization of the water cycle is not the best in these models as yet. Also, until very recently, GCM outputs are for equilibrium states whereas the hydrological events of interest, i.e. floods and droughts, are extreme events which are not found in the equilibrium state.

The last method I wish to comment on is a combination of the above which has become a popular technique. This method uses GCM outputs to provide the projected change in temperature and precipitation in increased CO_2 scenarios which are then used as input in hydrological models. Supposedly, the coarse spatial resolution of the GCM is improved as well the modelling of the hydrological processes. However, the problems with the possibility of extrapolating the hydrological model beyond its calibrated range and analyzing only the equilibrium state still remain. In addition, the physical basis of the models may be diluted since such work is not usually done by the developer of the GCM or the hydrological models but by a third party who in turn will provide his results to the socio-economic modelers to do projections on the potential impacts. These impacts are then finally presented to the lay person and politicians so that the scientific knowledge decreases each at stage.

The above are some of the problems I see in the present techniques being used in studies of future droughts and climate change impacts in general. These problems are to some extent, the result of the limits in the state-of-art which further research and development should alleviate. The availability of transient runs from GCM which will provide a more appropriate data set to examine extreme events is a step in the right direction.

Table 1

AES CLIMATOLOGICAL ARCHIVE -- STATION DATA

CANADIAN T & P STATIONS (DAILY):

≥ 50 YEARS RECORD	575 STATIONS
≥ 100 YEARS RECORD	56 STATIONS

AVAILABILITY:

9 TRACK MAGNETIC TAPE
MS-DOS FORMAT FLOPPY DISKETTES

CONTACT:

M.S. WEBB -- CANADIAN CLIMATE CENTRE

Table 2

AES CLIMATOLOGICAL DATA -- GRIDDED DATA SET

COVERAGE:

40° -- 90° N LAT 50° -- 150° W LONG	(CANADIAN LAND PORTION)

GRID:

SOUTH OF 70° N LAT	2° LAT x 4° LONG
NORTH OF 70° N LAT	2° LAT x 8° LONG
AT 50° N LAT	280 Km x 230 Km
AT 70° N LAT	320 Km x 230 Km

DATA:

256 GRID POINTS

DAILY AND MONTHLY (1951-80):

- T_{max}
- T_{min}
- T_{mean}
- PRECIPITATION

AVAILABILITY:

9 TRACK MAGNETIC TAPE

MS-DOS FORMAT FLOPPY DISKETTE?

CONTACT:

H. HENGEVELD--CANADIAN CLIMATE CENTRE

Table 3

GCM -- OUTPUTS

MODELS:

- GODDARD INSTITUTE OF SPACE STUDIES--(GISS)
- GEOPHYSICAL FLUID DYNAMICS LABORATORY--(GFDL)
- OREGON STATE UNIVERSITY--(OSU)
- ATMOSPHERIC ENVIRONMENT SERVICE--(AES/CCC)

GRID RESOLUTION:

	°LAT	°LONG	WINDOW
GISS	7.825	10.00	19.57--74.35 ° N LAT 50.00--180.0 ° W LONG 8 x 14 GRIDPOINTS
GFDL	4.450	7.500	20.0--73.3 ° N LAT 45.0--180.0 ° W LONG 13 x 18 GRIDPOINTS
OSU	4.000	10.00	22.0--74.0 ° N LAT 50.0--180.0 ° W LONG 14 x 14 GRIDPOINTS
AES/CCC	3.750	3.750	

Table 4

GCM -- OUTPUTS

DATA:

MONTHLY STEADY STATE MODEL OUTPUTS FOR 1xCO_2 CONTROL RUN AND 2xCO_2 ATMOSPHERE.

ABSTRACTED MODEL OUTPUTS INCLUDE MONTHLY VALUES OF:

TEMPERATURE	^{o}C
VECTOR WIND SPEED	M/SEC
PRECIPITATION	MM/DAY
MIXING RATION	$* 10^{-4}$
SURFACE RUNOFF	MM/DAY
INCIDENT SOLAR RADIATION	W/M^2
TOTAL CLOUD COVER	%

AVAILABILITY: (GISS, GFDL AND OSU)

9 TRACK MAGNETIC TAPE

MS-DOS FORMAT FLOPPY DISKETTE

CONAN ANALYSES ON AS/9060

CONTACT:

T. AGNEW--CANADIAN CLIMATE CENTRE

Table 5

SAMPLE GCM OUTPUT

TEMPERATURE (DEG C) **PREDICTED VALUES FOR 1xCO$_2$** **MONTH : JULY**

MODEL : GISS

LONGITUDE

	180.0	170.0	160.0	150.0	140.0	130.0	120.0	110.0	100.0	90.00	80.00	70.00	60.00	50.00
LAT														
74.35	00.28	00.24	00.43	00.23	-0.26	00.08	03.45	03.56	01.96	04.39	03.33	00.76	01.02	-0.31
66.52	11.90	07.90	13.87	13.79	12.76	12.48	12.23	13.63	11.16	09.40	03.96	08.14	03.69	02.52
58.70	09.61	09.57	12.38	11.64	10.84	11.49	12.82	12.88	13.29	04.75	04.49	09.62	06.82	07.11
50.87	10.38	10.37	11.86	12.13	12.82	15.01	13.73	15.47	16.51	18.39	16.17	16.06	14.41	09.40
43.04	14.68	15.94	15.26	16.51	15.77	17.43	17.13	13.08	16.74	18.51	18.80	19.76	19.45	14.06
35.22	23.66	22.25	21.18	20.88	19.32	16.90	21.93	18.97	19.66	26.87	23.14	25.30	25.65	23.22
27.39	26.00	24.47	23.26	22.71	21.00	19.55	19.13	27.83	23.31	27.40	27.45	26.27	26.19	25.66
19.57	26.72	26.24	25.96	25.38	24.09	22.50	21.72	24.32	25.12	27.44	27.61	26.72	26.50	25.24

TEMPERATURE (DEG C) **PREDICTED VALUES FOR 2xCO$_2$** **MONTH : JULY**

MODEL : GISS

LONGITUDE

	180.0	170.0	160.0	150.0	140.0	130.0	120.0	110.0	100.0	90.00	80.00	70.00	60.00	50.00
LAT														
74.35	00.29	00.25	00.59	00.42	-0.10	00.15	03.83	04.40	02.15	05.17	05.19	03.52	03.53	00.53
66.52	14.65	13.08	16.55	14.99	13.73	12.86	11.64	12.95	11.74	11.07	04.97	09.49	06.40	04.22
58.70	15.09	15.25	16.69	15.73	14.12	14.45	15.29	16.36	17.34	08.82	08.85	11.83	10.73	10.84
50.87	14.81	14.92	15.41	15.67	16.67	18.86	15.80	18.09	19.54	20.99	18.60	18.62	17.63	13.59
43.04	18.90	19.69	18.18	19.20	19.01	21.27	20.45	15.83	20.32	20.65	23.01	23.25	22.55	18.95
35.22	27.07	26.74	24.64	22.90	21.82	19.66	26.73	21.94	24.04	30.60	26.17	29.40	28.48	26.85
27.39	29.63	28.90	26.32	25.12	23.99	22.50	22.72	31.28	27.26	31.56	30.51	29.37	29.35	29.11
19.57	30.05	29.38	29.08	28.30	27.32	25.27	25.07	27.27	29.18	31.02	30.83	30.06	29.41	28.50

Figure 1

DATA SETS FOR STUDYING FUTURE DROUGHTS

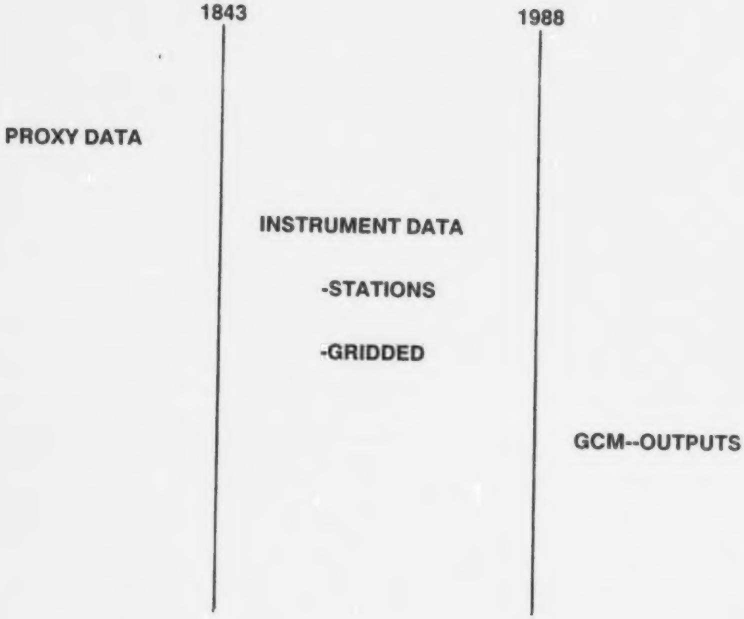
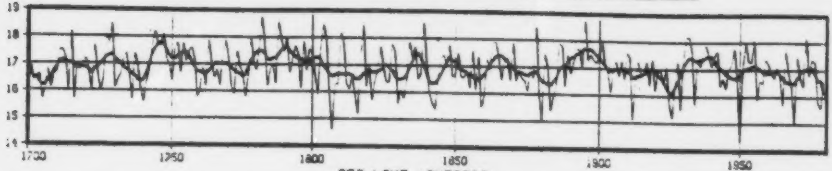
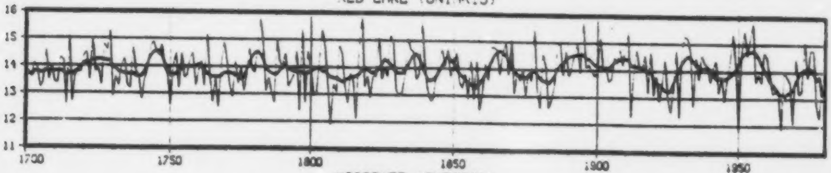

1843
1988
PROXY DATA
INSTRUMENT DATA
-STATIONS
-GRIDDED
GCM--OUTPUTS

Figure 2

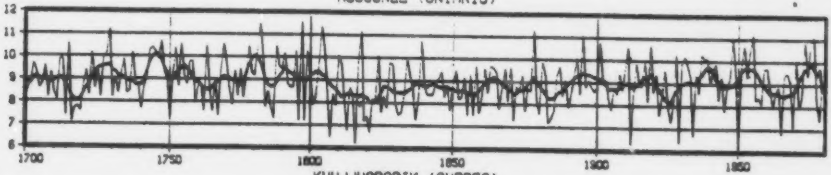
RECONSTRUCTION OF SUMMER TEMPERATURE (°C)



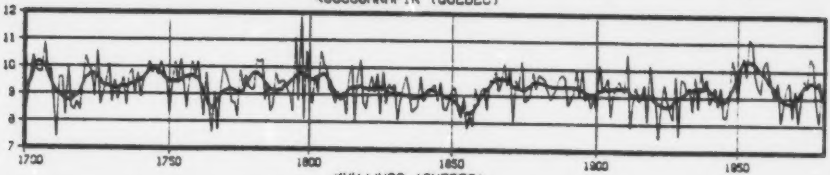
RED LAKE (ONTARIO)



MOOSONEE (ONTARIO)



KUUJJUARAPIK (QUEBEC)



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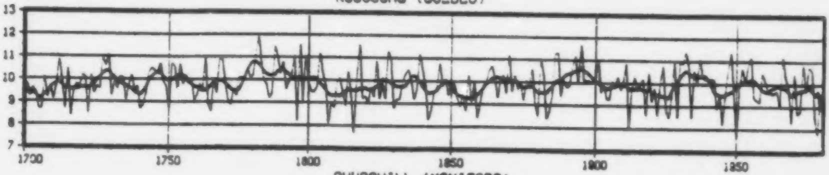
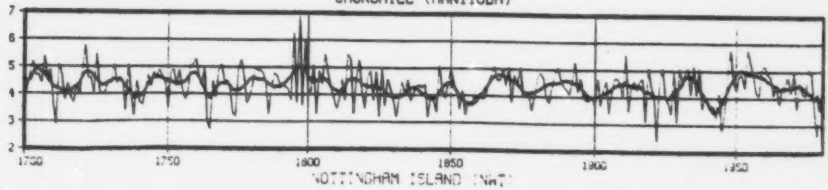


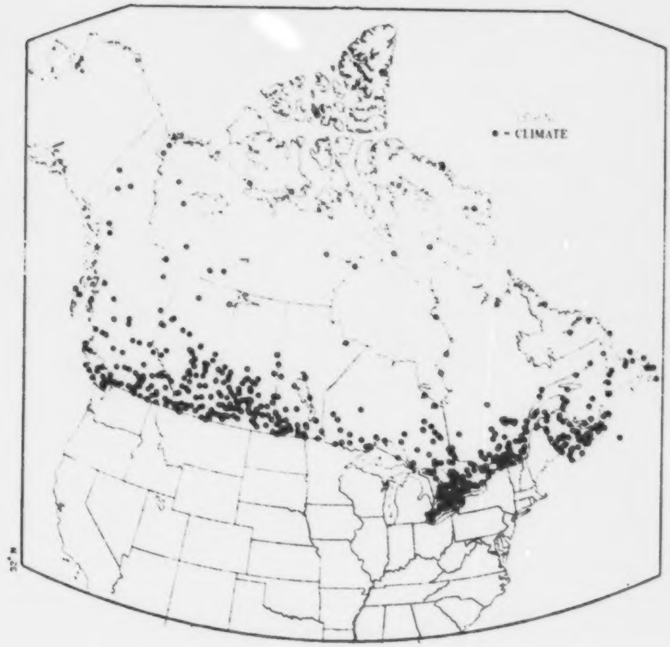
CHURCHILL (MANITOBA)



NOTTINGHAM ISLAND (NWT)

Figure 3

(a) STATIONS WITH MORE THAN 50 YEARS RECORD


LEGEND
● - CLIMATE
32° N

(b) TIME-SERIES OF MONTHLY PALMER DROUGHT INDEX
REGINA, SASK

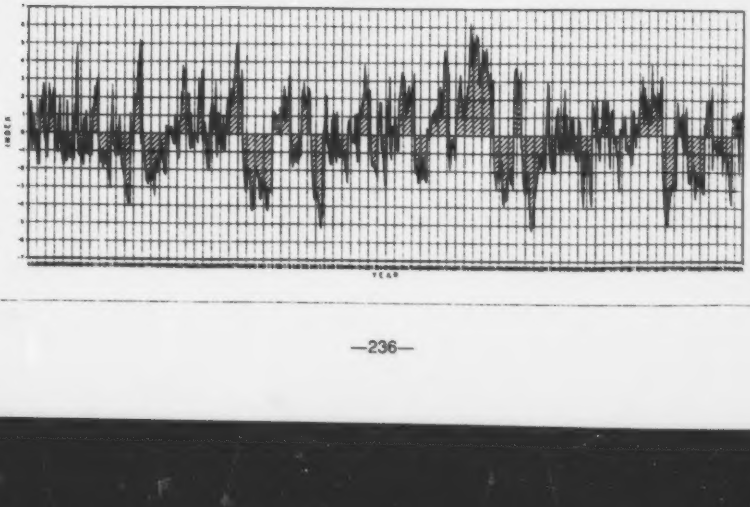
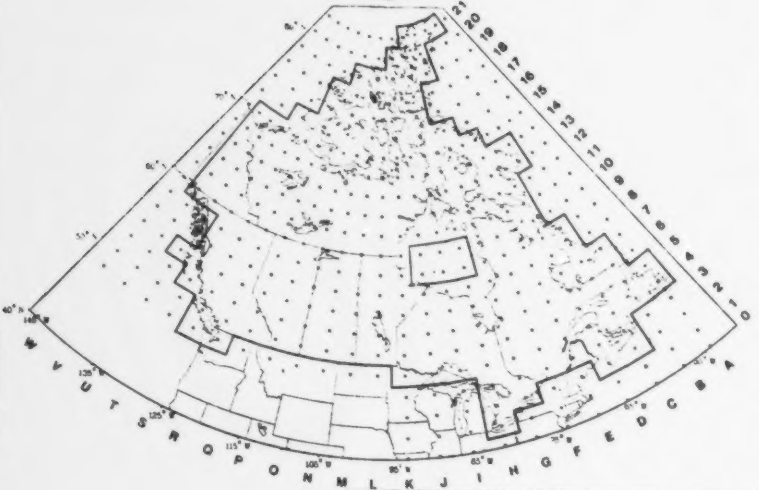


Figure 4

AES CLIMATOLOGICAL DATA -- GRIDDED DATA SET

GRID POINTS FOR CANADIAN CLIMATE DATA BASE

Map 1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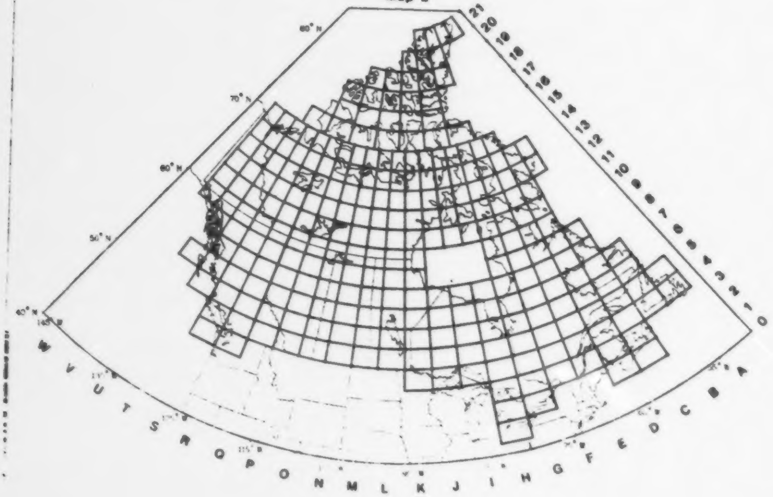
70° N
80° N

GRID AREAS FOR CANADIAN CLIMATE DATA BASE

Map 2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PRAIRIE DROUGHT AND CLIMATE CHANGE

by

D.G. Schaefer
Atmospheric Environment Service
Winnipeg

Introduction

Are current drought and droughts during the 1980s related to long-term climatic change and, in particular, to an enhanced greenhouse effect brought about by human activity? The question was an often repeated one during 1988. As a public agency responsible for meteorological services in Canada, AES was required to respond. That response was provided both to the media and to various user groups through such vehicles as the Prairie Farm Rehabilitation Administration's "Prairie Water Supply Conditions Report" (1988).

Factors

Recently published hemispheric and global surface temperature trends over the period from the late 1800s to the present (Jones, 1988, and Hansen and Lebedeff, 1988) have provided evidence of warming on a global scale. Published results based on atmospheric general circulation models (GCMs) imply more frequent and possibly more severe droughts in the future. For example, Manabe and Wetherald (1987) indicated mid-continent soil moisture losses in summer. Williams et al (1988) carried out analyses of Palmer Drought Indicies (PDIs) under doubled carbon dioxide scenarios. Results indicated significantly increased frequencies for droughts of any given severity.

A plot of Palmer Drought Indicies for Regina from 1905 to present reveals an oscillatory pattern without obvious periodicities. On at least four previous occasions PDI values dipped below -5, a level indicative of severe drought. Similar results obtain at other prairie locations. In an unpublished study, Guezen and Raddatz (1988) compared the dry decades centred in the 1980s and the 1930s. The two periods were found to be comparable with respect to the frequency of dry years, the intensity of the dry periods and the extent of the area affected, with only minor differences from one period to the other for specific measures.

Conclusions

1. Drought in the 1980s is not without precendent.

2. It can be "explained" within the context of natural variability.

3. It is too soon to tell if current drought conditions indicate a climate change.

4. Despite the above, 1988 has been considered to be "a teachable moment" or, indeed, "a dry run" of conditions that may become more prevalent in the future under the influence of the changing atmosphere.

References

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Hansen, J., and S. Lebedeff, 1988: Global surface air temperatures: update through 1987, Geophysical Research Letters, Vol. 15, No. 4, Pages 323-326, April, 1988.

Jones, P.D., 1988: Hemispheric surface air temperature variations: recent trends and an update to 1987, Journal of Climate, Vol. 1, Pages 654-660.

Manabe, S., and R. Wetherald, 1986: Reduction in summer soil wetness induced by an increase in atmospheric carbon dioxide. Science, Vol. 232, Pages 626-628.

Prairie Farm Rehabilitation Administration, 1988: Prairie Provinces Water Supply Conditions Report Updated to July 13, 1988, Regina, July 15, 1988.

Williams, G.D.V., R.A. Fautley, K.H. Jones, R.B. Stewart and E.E. Wheaton, 1988: Estimating effects of climatic change on agriculture in Saskatchewan, Canada, IIASA, Austria. Summarized in Climate Change Digest CCD 88-06, Environment Canada, Atmospheric Environment Service, Canadian Climate Centre, Downsview, Ontario, July, 1988.

Session 4 - Working Group Questions and Issues

General

Working Groups can choose to address one or two of the following questions and issues, or adapt them, or devise their own questions.

4.1 Climatic Warming Certainty

Is there currently a scientific consensus that the anthropogenically generated climatic warming will lead to more frequent and more severe droughts in the Prairies? Should the researchers in the field promulgate public statements to that effect? Should this Workshop, or others (after careful consideration), recommend that responsible authorities make specific adjustments and develop programs in anticipation of the worsening droughts?

If not, what combination of events and research results would lead to sufficient confidence a) among the researchers (who presumably would be the issue leaders) and b) among the authorities?

4.2 Assessing Climatic Change Impacts

What research is required to enable useful assessment of the potential impacts of climatic change on the frequency and severity of droughts in the Prairies? Address the need for understanding of fundamental processes as well improving methods for conducting climatic change impact studies.

4.3 Improvement of GCMs for Climatic Warming Impact Forecasting

What improvements/changes need be made to the GCMs to provide the capability of predicting the climatology of drought in the assumed future altered atmosphere? What priority should be placed on allocation of resources to these efforts relative to climatic change impact studies?

4.4 Assessment of Recent Climatic Trends

Is the series of droughts in the 1980s the result of climatic change, and, specifically, the result of anthropogenically induced climatic warming? Should we first look for the "signal" of climatic warming in the means of climatic parameters, or in the extremes such as droughts?

4.5 Climatic Variability Impact Studies

Considering the uncertainty of estimation of the impacts of drought on the various socio-economic systems, do we have adequate capability to assess these impacts even if we had a perfect prognosis of future climate? What level of effort should be made to improve this situation, and by whom?

Do we have adequate understanding of the impact of current climatic variability for policy making and drought response program delivery ?

4.6 Specific Studies

Can you suggest specific research projects which should be performed in the near future to concretely address specific questions about climatic warming? Elaborate.

4.7 Abrupt Transition to a New Climate

Is it reasonably possible that the transition to a new climatic regime associated with higher levels of radiatively active gases would occur abruptly rather than gradually? Is there strong evidence of past abrupt climatic change, and is this worth further investigation? Consider the rapidity of the development of the "ozone holes".

What implications does this have for research into the transitional drought climatology on the way to a 2 X $C0_2$ atmosphere, as opposed to a 2 X $C0_2$ steady state climatology?

DROUGHT IN THE FUTURE

Summary

J. Maybank - Session Chairman

A total of seven topics was presented to the seven working groups into which the participants had been divided. They were requested to address only one or two of these in the time available, but were not constrained to any particular items. As a result, some topics were discussed by four or five groups who each produced specific conclusions and recommendations, while other topics received less attention, and two received none.

These topics and the responses prepared by the groups that discussed them are as follows.

4.1 CLIMATIC WARMING CERTAINTY

This topic or the possible connection between climate warming and drought prevalence was addressed by five of the seven working groups. A point summary of their concerns and conclusions follows:

(i) There was general agreement that a world wide warming trend has now been identified, but it cannot be unequivocally attributed to human activity or even greenhouse gas emissions, natural or anthropogenic. Overall precipitation levels appear, at the moment, likely to remain similar to present day patterns.

(ii) While there was no consensus that drought frequency would increase with the warming trend, there was certainly concerns expressed for the possibility. One group thought it might, while others pointed out that there would not likely be any such one-to-one correspondence. Furthermore, no change in the past frequency of droughts is apparent from the record.

(iii) As to drought severity or intensity, it was felt this might increase, perhaps through the lengthening of the frost free season. Again, there is no evidence yet of such an effect.

(iv) For both warming and drought occurrences regional variations appear very likely, and so far are not being addressed, as the models are too "coarse-grained."

With regard to recommendations the following actions may be identified:

(i) Drought planning should be given more focus, regardless of projected climate change. The federal and provincial governments should formulate and implement an integrated and sustained program for coherent investigation of promising drought mitigation measures, concentrating especially on the Palliser Triangle area.

(ii) There is a need to look for analogs of climatology, in such areas as farm practice and plant adaptation. These in turn can serve to improve research endeavours into such areas as water conservation, plant breeding and reservoir utilization.

(iii) Public acceptance is needed and for this to occur we need public awareness. Climate publications should receive wider distribution and circulation.

(iv) Researchers should make statements with due caution, emphasizing, wherever appropriate, the uncertainty of predictions. Joint, interdisciplinary statements and pronouncements should be encouraged.

The following two topics were not discussed by any of the working groups. The questions asked are given here for the purpose of record completeness.

4.2 ASSESSING CLIMATIC CHANGE IMPACTS

This topic was not dealt with by any of the working groups.

4.3 IMPROVEMENT OF GCM'S FOR CLIMATIC WARMING IMPACT FORECASTING

This topic was not dealt with by any of the working groups.

4.4 ASSESSMENT OF RECENT CLIMATIC TRENDS

This topic was addressed by one of the working groups. There was agreement that there is insufficient evidence to ascribe the droughts of the 1980s to climate change, let alone to anthropogenically induced climatic warming. The group members agreed that any search for the signal should be concentrated on the means or median values rather than on the extremes.

4.5 CLIMATIC VARIABILITY IMPACT STUDIES

It was agreed by all four groups that tackled this topic, that even though we lack a full understanding of drought causes, and are a long way from reliable climate prognoses, socio-economic impact questions must be addressed.

Projection of impacts is rendered very difficult due to changes in the economy, technology, and farm practice. Important factors other than drought must be included, but it is necessary to isolate drought effects from others such as world markets. Despite the difficulties, impact studies are needed.

Social and economic aspects do not always need to go together; the former are generally more difficult to address, so priority should be given in some cases to the latter. Further specific recommendations on this need for impact studies were:

(i) concentrate on those areas of most signal effect;

(ii) comparison with areas not affected by drought can be useful;

(iii) types of drought are a concern, and impact studies should distinguish between multiple and sequential droughts;

(iv) the "ripple" effect through the entire economy should be investigated;

(v) use models which give response functions and develop the latter, based on past drought;

(vi) identify in particular regional aspects, leading towards an integrated land policy on a regional basis.

The answer to the last question in 4.5 was a categorical "no!" from all groups. A coherent and sustained impacts analysis activity, should, however, lead to an overall Drought Strategy Program, which would be an appropriate component within the general International Decade on Natural Hazards (IDNH) program.

4.6 SPECIFIC STUDIES

On the expectation that any anthropogenically-caused climate warming trend will be most pronounced at northern latitudes, it is here that early manifestations should be sought. The following specific research needs, were identified by the two working groups that addressed this topic.

(i) Set up an increased monitoring system in northern latitudes to detect climatic trend signals, specifically guiding the program by GCM requirements.

(ii) Increased monitoring of downward-moving long wave radiation is required, linked with remote sensing observations and archived satellite data to identify effects on and of the greenhouse gases.

(iii) There needs to be a national soil moisture field monitoring network, leading to a forecasting methodology for input into climate modelling.

(iv) There should be increased support for theoretical studies into the causes of climate warming (e.g. ENSO events, etc.) which can be tested with existing data or models. Improvements to GCM's are required to enable them to mimic actual (past) observed conditions. Development of mesoscale models should also be pursued to investigate regional expectations.

(v) Research should be directed towards improving the AES-CCC model so as to accurately forecast precipitation.

In these research endeavours and for others that will arise, there should be increased emphasis on interdisciplinary aspects, as drought is not solely a meteorological problem.

4.7 ABRUPT TRANSITION TO A NEW CLIMATE

The one group that discussed this topic felt there was no evidence as yet that a greenhouse gas induced warming would not be gradual on average. However, past climate history, for both the little ice age and for earlier altered climate episodes indicated that step-type changes do occur. Therefore, it cannot be concluded that a gradual increase from a CO_2 level of 350 ppm to one of 700 ppm will be accompanied by a commensurate steady change in mean air temperature, and the possibility exists of an abrupt upward shift in global temperatures during this, or some future, decade. There is clearly more research needed into the carbon cycle at least before this question can be adequately addressed.

In conclusion, it cannot yet be stated that drought frequency or severity would increase with an anthropogenically generated climatic warming. Nevertheless, it was accepted as absolutely certain that there would be major droughts in the future. As in the past, such droughts would severely strain agriculture and forestry within Canada, and have a significant detrimental effect on the entire national economy. What is clearly needed is not a crisis-oriented drought mitigation activity at the time of their occurrence but an ongoing, coherent and sustained research program into all aspects of drought. Such an effort, if properly funded, focussed and maintained, will provide the insight necessary to identify the future course of a new drought, and to mitigate its effects more effectively than was possible for its predecessor.

SUMMARY AND RECOMMENDATIONS

PRAIRIE DROUGHT WORKSHOP

SASKATOON - 11-13 October 1988

SUMMARY COMMENTS - "NO DROUGHT OF IDEAS OR CHALLENGES"

E.F. Roots

It is my final job as Chairman to say a few words about the workshop as a whole - what we seem to have accomplished, and what we have left undone. It was my pleasure to circulate among the different sessions, to get an impression about what was going on, and to listen to the statements and the arguments. I suggest that we think about what we have achieved by asking ourselves a few questions.

1. DID WE ACCOMPLISH OUR OBJECTIVES?

You have the workshop objectives as listed in the yellow papers in front of each of you. I suppose there is a corollary to this first question, which is:- "did we find that the objectives were realistic?" Was this meeting a useful vehicle to (i) "transfer new knowledge and technologies to users, (ii) to review new knowledge and research needs, and (iii) to serve as a forum for identifying opportunities for collaboration"? I think, from my point of view, the honest answer must be that the objectives as written were only partly met. With regard to the first objective, I am not sure that we made any real progress in transferring new knowledge and new technologies with regard to drought prediction, monitoring and management, to the users. Either we concluded that this is not possible to do, or the present state of the art and the knowledge level and the communication skills of both the researchers and those who need the information are not yet ready for it. So, those who came to this workshop hoping that science would reveal some new magic formula that will make the next drought easier to predict and manage will have to go home disappointed. But, in my view, the workshop was very valuable in bringing us to this realistic point of view.

On the second objective, we did make real progress in reviewing the current research and identifying research needs. This thrust of the workshop was led by the keynote speakers, the poster papers and was stimulated by the leading questions from participants in the working groups. And given the general research orientation of the workshop, this is what most of us probably came for and expected, and it's pretty well what we got. There was, it seemed to me, a persistent and sustained attempt to place the research needs and results of research in the context of the practical value to the user, whoever the user might be, but this had very mixed results. I think that this partial failure was perhaps because there was limited research reported or apparently being undertaken into the range of options that are available to the user if he has more information. If the "user" is told what is wrong, but nobody can tell him what he can do about it, the science is not much good to him, and is not of much practical value.

With regard to the third objective, we noted many areas where collaboration in research would be desirable, but we gave little attention to identifying actual opportunities for collaboration or for using the workshop as a forum, or, as it was stated, for developing cooperative future plans. We seemed rather to end up with wish lists of what more research ought to be done and to make recommendations directed toward people who we hope have some money to support our future studies.

2. WHAT MAIN AREAS OF CONCERN EMERGED?

I think the four sessions and the poster papers nicely rounded out the obvious scientific questions that have arisen in the aftermath of the 1988 prairie drought. Collectively, we tackled three major questions. First, what do we know at present about the forces and the factors that give rise to a major drought and maintain it? Second, what do we need to know to get a better warning that a drought is coming and what do we need to do to get better information from it when it's here? How can we obtain and preserve the knowledge and experience from one drought so that it helps us to do better when the next one comes along? We did have some good discussions that were designed along those directions. And then the third question, "can we predict the occurrence and severity of the prairie droughts?" We faced that question fairly honestly and said "No".

What we did not do, or even attempt seriously to do, was to develop answers to the kinds of questions that most frequently are asked by the public during the time when they must take action in drought - the kinds of questions that Garry Schaefer talked about this morning. We realized that drought scientists and environmental and agricultural authorities needed to be in a position to do this; but this particular workshop didn't do much about it.

3. WERE THE SUBJECT SESSIONS AND THE WORKING GROUPS A GOOD WAY TO ADDRESS THESE CONCERNS?

Each session has been ably summarized by the session chairman. I am not going to attempt to make any comments on their comments; it would be presumptious, and anyway, their reports will be in the workshop proceedings. But it is my privilege to leave with you some personal impressions, both from listening to the papers and discussions and from my roving around, about what happened in the different sessions, and whether there is any coherence to the ideas that we ended up with. I will mention also some things that I thought we might have discussed but did not.

In a large multi-discipline workshop like this, the group dynamics is interesting. Because I had the unique chance of sitting in on each of your sessions, it was possible to note that each group soon developed its own character and interactions. It really is a measure how many-sided is the question of drought, that seven groups chosen more or less at random from a heterogeneous group of people, each addressing the same set of questions should develop seven distinct personalities. And just for fun - hoping I don't offend anybody here - I might with some exaggeration characterize the working groups as follows:

Working Group #1 acted like an intellectual coffee club. It wasn't afraid to tackle any subject and drop it when it got too hot or too difficult to do anything else with it.

Group #2 was the noisiest by far. Their discussions really took on the characteristics of a morning-after postmortem and they scared each other by asking - "by God, where do we go from here?"

Group #3 I think was perhaps the most skeptical of the groups. It was a bit of an iconoclast sometimes and the group worked this mood inward on itself despite a few people who really tried hard to say - "Come on, we know more than you admit that we know, and the situation is not hopeless". But ideals and optimism were in short supply in their discussions.

Group #4 ran more like an environmental assessment panel meeting, only everyone was on the panel and there were no intervenors or champions for or against drought. They assembled all the evidence and then disbanded.

Group #5 acted most like a university seminar and I learned a lot when I was in there.

I didn't know whether I believed it or not but I was taught something. There were a few professors, the rest were rather meek students who perhaps felt guilty because they had not done their homework.

Group #6 set itself up as a jury to weigh the evidence, one side or the other. But each time I dropped in, there seemed to be an impasse for lack of firm evidence.

Group #7, I think, was the most wide ranging because when it got started on something, each topic led to a new topic and then they had to scurry around and find some new comments. I don't know where they got to at the end.

This variety is interesting, because it shows that there isn't any single answer to our questions. Perhaps it showed collectively we all tried to be too simplistic - and yet that's the only way we can approach these kinds of complex and interlocking questions.

Every one of the Working Groups made a substantial contribution and added something real to our collective knowledge and understanding. Despite my light-hearted caricatures of the differences, I would not like to choose which was the most successful. The seven different approaches were all successful.

4. WHAT WERE SOME HIGHLIGHTS AND NEW IDEAS?

I have been asked by the organizers to review a few highlights of the Workshop as a whole. I have limited them to six so that we wouldn't go on and on; and that means that most people who have said something very substantial and important are not going to be included in these comments. But, for better or worse, here are some points that appear at this very short notice, to have had particular influence on our discussions and understanding as the workshop progressed; to me they are therefore highlights not in terms of quite new knowledge but in the way the ideas changed our collective thinking.

- Gene Rasmussen's classification of the sources of climatic and hydrological variability, and especially the idea of separating the stochastic events from the chaotic internal dynamics, had an effect on much of our subsequent discussion.

- Rick Lawford's clear setting forth of how the type of driving force was related to the scale of the cause and the scale of effect kept us on track - and that was really a very good contribution.

- I think Alf Warkentin's demonstration that good water resources management can do much to avoid or mitigate the cost of drought to institutions and utilities, but that the risks to individual farmers are still largely a matter of luck, helped to bring a sense of realism and common experience into what we were doing, and kept our science from being just an intellectual exercise.

- Professor Yevjevich's timely observation that climatologists and hydrologists speak different languages and use different assumptions while using the same terms for the same phenomena was a good warning to all of us who tend to take a narrow scientific approach to sophisticated studies; and his emphasis on the need to build on all the available base data but not trust any of it was very timely.

- I think Bill Klein's careful statistical analysis that linked upper air circulation, which has a large area of subjectivity, to surface weather and to soil moisture that can be more precisely measured but are more internally variable points the way that we are all going to have to go, in combining objective synthesis and subjective skills to increase our collective ability to handle these kinds of questions.

- This morning, Ken Hare's perspective, global in scope, asking us to open our eyes to what is happening to the planet and not be bemused by our studies of any particular little corner of it, and to recognize the growing and, to some people, rather frightening coherence from many lines of evidence from all parts of the planet as to what is going on, while being careful not to jump on the bandwagon of the moment of any particular interpretations or theory provided a good lesson and a perspective for us to take home with us.

5. WHAT COMMON THEMES WERE IDENTIFIED?

There were some common themes that emerged not from individual papers but from group discussions. One which was very nice and often all too rare was a theme of honesty, of admitting that we just don't have the knowledge and skills to predict. We have a consensual conviction, and the evidence is not contrary, but we cannot as honest scientists be confident that our consensus and studies are leading us to better ability to understand and predict drought.

Another theme centered around the question of the definition of drought. Despite my caution at the beginning not to get hung up on this question, for the first two days every person who stood at this podium presented his own definition. The definitions were more or less coherent, but I think none of them could improve on Alf Warkentin's definition, "drought is a period of dry weather that causes difficulties." If you include and accept that the dry weather can include dryness from a previous year or the previous winter, it picked up nearly all the questions we had. The idea that drought is a user or human concept and not a natural phenomenon was accepted. And if I may refer to my opening comments, you will note that several times yesterday, speakers made distinctions between drought, which is a transient phenomenon, and climate change or desiccation as Ken Hare called it this morning, which is either continual or longer term or irreversible. This was a useful distinction for us to keep in mind as we went into discussion of the other common themes.

A further theme that was common to many discussions had to do with the linkages between different "kinds" of drought. Most discussions and analogies of drought start with climatic and meteorological drought, modified more or less by antecedent conditions. This situation then leads to all the other "kinds" of drought. What are the linkages between them? In our workshop discussions, we jumped from climatic drought to hydrological drought to Professor Yevjevich's "user drought" and back again repeatedly. We said we would have to do some research to join these concepts; but it is not clear to me what kind of research that would be.

Certainly another common theme was the interdisciplinary nature of the research needed to increase our understanding and to improve the ability to transfer knowledge between branches of science, between scientists and policy people of the public. I need not elaborate, for this is central to many of the session reports.

Another theme that emerged from our discussions is that we still have a severe scale problem in dealing with drought in a synthetic way. For example, scale difficulties make it hard to relate what we know about temperature to what we know about precipitation. As drought is a function of current precipitation, residual soil moisture, and evapo-transpiration, which are strongly controlled by recent or current temperature, modelling encounters severe scaling and boundary problems in relating current precipitation, which particularly in periods of increasing dryness tends to be heterogeneous on small time and space scales, with former precipitation and residual moisture, which may be "averaged" by groundwater, and to relate these to current or recent temperature history. With most drought studies, we seem to be still at the stage where increasing refinement leads to greater complexity and confusion, and have not yet reached the stage where a leap in understanding or theory will provide the simplicity into which all new data will fall smoothly.

An important theme had to do with the international and global connections of all drought-related events. Although drought is felt locally, its causes and controls are not local in origin. The fact that drought-related events had different degrees of importance to different groups, to different people, was another widely accepted theme.

The need for better data on soil moisture came out many times and I am glad that Ted O'Brien emphasized this in his final comments.

And then there was another set of common themes that had to do with the need for better communication of drought related information. Our thinking along these lines started with the presentation that Jim Laver gave about what is happening in the United States in terms of developing the ability to respond to different kinds of needs in an organized way that brings a lot of agencies together when necessary. The experience in developing this ability shows that it is necessary to educate politicians and decision makers even more than it is necessary to educate the farmers and the residents about the chances of the likelihood of drought, what it will be like when it occurs, and what can be done about it.

I think there is emerging, but not very often clearly stated, the need for people concerned with scientific aspects of drought to work systematically toward acceptance of uncertainty and not look for black and white answers, for much improvement in abilities to predict the onset of drought or its duration. Although we talked a lot about refining numerical probabilities, what we seemed to be searching for was a flexible approach. In one of the groups we talked about realistically trying to get politicians to adopt or apply the "Genesis Strategy", as Dr. Stephen Schneider of the National Centre for Atmospheric Research urged the U.S. Congress to do. (Schneider, 1983). The Genesis Strategy, taken from Chapter 41 of the Book of Genesis of the Bible, recognizes that there will be a crop failure due to natural causes after a period of productive years (the Bible says, symbolically, seven years), but which year is not predictable; and a wise country puts aside sufficient produce and seed from productive years to tide over the non-productive year. Modern economic planning can make such a strategy very efficient, and less wasteful than schemes to prevent losses. Related ideas emerged from several groups.

6. PRIORITIES AND ARRANGEMENTS FOR FUTURE RESEARCH

Many high priority subjects for research were identified. Some will be in the proceedings. In many ways these focussed around interdisciplinary research on a local basis, and then joining that research to studies of larger issues of global change and geosphere-biosphere interactions. The questions that Elaine Wheaton brought up this morning on studies of the behaviour of people to the 1988 drought in the Canadian Prairies would seem to me to fit very directly into the UNESCO Man and the Biosphere Programme, which has as one of its four main international research orientations, "The Human Response to Environmental Stress". Perhaps Canada could make a significant contribution to that programme, and bring the benefits of the international UNESCO studies to our problems on the prairies, if we seriously looked at the issues of prairie drought in the context of the UNESCO researches.

7. AREAS NOT TOUCHED ON OR WHICH RECEIVED LITTLE EMPHASIS

There are some areas though, that seem to me to be important to drought research, but which had little or no emphasis at this workshop. There was relatively little attention given to the analysis of the severe drought conditions in the last year or so, in relation to the normal and anomalous synoptic mesoscale weather patterns. People always assumed knowledge of such relations as background, which in the discussions the other person must know all about; and this may be true. But as far as relating the weather patterns to the drought patterns, we didn't seem to think that a careful analysis was a very important thing to do. I'm surprised. The teleconnections seemed to be examined as mostly statistical or numerical problems, not as processes to be understood; and that was rather interesting, because, if we are going to make teleconnections we should know something about the physics of what goes on, the energetics.

On the whole, there was surprisingly little analysis of the regional and local energetics of drought; of what was the difference in energy flow and material flow in an area being subjected for a few weeks or a few months to unusual dryness, both within the biological system as well as within the meteorological and hydrological systems, compared to the normal. And yet an understanding of the nature of anomalous energy distributions and fluxes is, I think, an important part of understanding of drought. We talked, for example, about El Nino and what its connection with prairie drought might be, but El Nino is first and foremost a temporary instability in ocean energetics; and it is the energy instability, not the coolness or the warmness, that appears, from what we know about global physics, to trigger events around the world. We didn't discuss the questions of the larger and smaller scale drought phenomena in those kinds of terms.

In the same manner, drought is at one end of a set of conditions that range from dryness to extreme moisture and floods. Sometimes droughts and floods occur closely related as happened in Sudan this year. We didn't really look at the other end of the scale to see what can be learned from it; that omission is rather interesting.

There was also, a surprising lack of attention to the lateral and downwind conditions during drought events. We kept on looking upwind to the source, to what appeared to be happening in the North Pacific, which is important. But despite all the good work that John Knox has been doing on atmospheric blocking processes, the workshop did not take the next logical step and consider that if a condition is anomalous and held stationary, something beside it or downwind from it must be holding it there or blocking it. Examination of these possibilities suggests not study of the North Pacific, but of the patterns of jetstreams and blocking highs in southern North America or the North Atlantic, yet I did not hear discussion of this. Nor did I hear research proposed to study what is containing the dry air? What would be needed to disperse it? It is rather interesting that our discussions did not seem to run in that direction at all.

We didn't really look, as scientists, into better means of taking small scale variations into account in converting meteorological drought into agricultural drought. Some of the questions that Ted O'Brien just mentioned with regard to soil moisture surveys are obviously parts of that. Nor did we really look at whether we should do experiments on moisture transfer and variability; whether or not there is a good relationship between our various small scale, middle scale and large scale models. There seemed to be nobody who was really campaigning, until the very last items this morning, for a careful study of historical sequences of conditions that maintain drought or trigger its ending. We seem to be bemused by the onset of dryness, but not by the conditions that maintain it or cause it to disappear. In fact, as someone said, when it starts to rain you forget about all the things that were so important the day before, and lose the experiment that's going on.

There was little attention to the effect of drought on water quality except when you mix it with bourbon; but the rest of the time we seemed to ignore it. And yet, drought is one of the important factors in the whole water quality question on the prairies. The bridging between GCMs, regional hydrological models, and soil process models, was mentioned by Paul Louie this morning as something for which we collect data; but we didn't look on such bridging as a way to approach our problems during our general discussions.

And then, finally, I was very happy to see this morning that Mel Berry and Elaine Wheaton brought us back to the need for research on economic, socioeconomic, and human behavioural aspects of drought. But what was interesting is that in the group of people here, everyone seemed to think that such studies ought to be done; however I didn't hear anybody say that these subjects already are important areas of research amongst the economists, planners and so on. We do know that there are a lot of people interested in research in these fields. Is none of it going on in Canada? Are the social science researchers not communicating with the natural scientists? Is our lack of knowledge of drought research in these fields only a reflection of the group of people we had at this workshop, or is it a sign that no research is being done?

8. WHAT HAPPENS NEXT?

That observation leads me to the last item I'll make comments on here. What happens next? Certainly there are some areas where, in the recommendations, it will be important that we act quickly and get planned study proposals on the kinds of problems that have emerged from this discussion, on a purely research basis, into some of the larger international study programs. That is necessary not only from the funding point of view, but from the point of view that now we have a sober idea of how little we know about some vitally important issues, and what are the areas in which we can make rapid progress. Also, there are a lot of other people around the world thinking about the same kind of problems, and they are very anxious to have us join their teams.

So, with IGBP, the Man and the Biosphere Program, the International Decade of Natural Hazard Reduction; these programs are underway just at the time when, if we have any good scientific ideas that arise from or for prairie drought studies, we would be welcomed. Our workshop also pointed out the very urgent need for amalgamating in a better fashion than we do at present, Canadian and U.S. prairie hydrological and climatological data. I think we can make a start on that rather quickly, within the authorities of the data-gathering agencies on each side of the border. We have also identified in discussions, a need to make much better known the benefit/cost ratio of better monitoring and of being able to make the information more accessible and widely distributed.

I think that one of the obvious follow-up points is that we must take advantage of this inadvertent experiment that was conducted in the prairies this last year. We must find the interested people and the resources to undertake studies, before the evidence is lost, not only into the hydrology and the effect on agriculture, but into the effect on natural ecosystems and human institutions. The Workshop did not pay much attention to the natural system, although there are some people here who are very concerned about it. Certainly, we need to get going right away, if it seems at all sensible, a socioeconomic study of the effects and responses to drought and of the individual and institutional actions that have been taken during a drought and learn from the recent experience, so we will have better knowledge and advice for the next one. From that point of view Elaine Wheaton has suggested anyone who wants to carry these ideas further meet her right after we adjourn the workshop.

So all in all, I think we had 2-1/2 good days. I think each of us goes back with a bit broader perspective and a little bit more humility about how far, and yet what a short distance, science has taken us. It is too bad that Dr. James Hector could not have been with us. I think, from the perspective of 120 years ago, he would have enjoyed our discussions.

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RECOMMENDATIONS

Research:

1. Research into developing the physical/dynamical model approach to drought forecasting should be expanded. Such research should be interdisciplinary and must include interactions between sea and land processes and atmospheric dynamics as related to the onset, termination and severity of droughts. At the same time, research should continue into developing statistical/empirical approaches to drought forecasting.

2. There should be increased support for theoretical studies into the causes of climatic warming (e.g. ENSO events, etc.) and for improvement to the hydrologic component of GCMs including the effect of man's influence (e.g. land use changes). In particular research should be directed to improving the AES-CCC model so as to more accurately forecast precipitation.

3. Research is needed to identify the processes which initiate and terminate a drought and to assess the relative importance of each of these processes. In addition to studying physical/ dynamical and stochastic processes the role of anthroprogenic factors should be examined and evaluated. Paleoclimatological data and ocean sediment cores should be used to extend the record available for studying Sea Surface Temperatures and prairie drought.

4. Meteorological droughts should be quantified with respect to their spatial and temporal distributions and their intensities. The linkages between meteorological droughts and other "drought types" need to be defined. Issues to be resolved include the following questions:
    - Are multi-year droughts discrete events or a succession of seasonal droughts?
    - How do stochastic processes affect the development of a meteorological drought?
    - What role does antecedent precipitation (fall soil moisture reserves and snowpack) play in alleviating the effects of a meteorological drought on agriculture and water resources?
    - What is the effect does timing of precipitation have on agricultural and hydrological droughts?

5. Research in the area of remote sensing applications to monitor snow depth, water equivalent and soil moisture should be encouraged.

Public Education:

1. The Atmospheric Environment Service should take the lead in educating users and potential users of long-range atmospheric forecast products by:

a) documenting all scientifically reputable medium-range (5 - 15 days) and long-range (16 - 90 days) forecast products available to Canadians and describing for each one:
  - its availability;
  - methodologies used in preparation
  - accuracy including comparative verification statistics for similar products; and
  - how to best interpret and utilize each product with particular reference to drought forecasting.

b) cautioning users against the use of scientifically-unfounded long-range forecast products.

c) discussing the potential for future improvements in the field of long-range weather and climate forecasting.

2. Public acceptance of the potential for climate warming and the resultant consequences is needed and for this we need public understanding and awareness. To help achieve this it is recommended that:
- climate publications receive wider distribution.
- researchers make statements with due caution, emphasizing, whenever appropriate, the uncertainties of climate change and its effect on drought frequency.
- drought specialists clarify the type of drought they are referring to, especially when communicating with the media.
- joint, interdisciplinary statements and pronouncements concerning drought be encouraged.

Policy:

1. Drought planning should be given more focus, regardless of projected climate change. The federal and provincial governments should formulate and implement an integrated and sustained program for coherent investigation of promising drought mitigation measures, concentrating especially on the Palliser Triangle area. In order to achieve this a better understanding of the long-term effects of drought mitigation policies on land management is required.

2. Even though we lack a full understanding of drought causes, and are a long way from reliable drought prediction, socio-economic impact questions related to climate variability must be addressed. Such impact studies should distinguish between single

and sequential droughts and should investigate the "ripple" effect through the economy. Model response functions based on previous droughts and regional aspects of drought should be used to develop an integrated, regionally based land policy.

Monitoring:

1. On the expectation that any anthropogenically caused climate warming trend will be most pronounced in northern latitudes we should undertake increased monitoring (including downward long wave radiation and soil moisture field monitoring) over Canada to detect climatic trend signals.

2. There is a need for standardization, among the many agencies involved, of data gathering and dissemination. It is recommended that a multi-agency data management plan be devised which includes network design and standardization, data quality, inadequacies in existing networks, supplemental networks, remotely sensed data, automation and data communication and access.

3. Although the P.D.I. and C.M.I. are not perfect, they should be maintained and users educated as to their application.

4. There is a need for a common definition of drought. A holistic drought index would be ideal, but in view of the difficulties in developing such an index it is recommended that the primary drought index used be for a meteorological drought. Such an index should quantify meteorological droughts according to extent (temporal and spatial), intensity and timing (beginning and ending) and in some way take into account the effect of multi-year droughts. Based on this index of meteorological drought linkages between meteorological drought and other types of drought should be defined.

POSTER PAPERS

MONITORING THE 1988 PRAIRIE DROUGHT

by

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Abstract

Wet and dry regions across Canada are monitored using three simple tools - a trough/ridge (Hovmoller) diagram, a cumulative precipitation index (CPI), and a water budgeting procedure. These approaches provide information on the general features of atmospheric circulation, the availability of total water supply (meteorological) and the current soil moisture deficits (hydrological,) respectively.

Some results of our analysis of the 1988 Prairie drought are summarized by the figures below.

1. Background

Water is a vital resource to a nation, and its excesses (floods) or lack of it (drought), can bring about much devastation socially, economically, and even politically. Because water is not distributed uniformly in space and time, monitoring its fluctuations is an important step towards any decision process relevant to water use and management.

At the Atmospheric Environment Service, Hydrometeorology and Marine division, monitoring of moisture surplusses and deficits starts with the assessment of average atmospheric circulation patterns using a Hovmoller diagram for 30 to 50 north (see Fig. 1a.). Combined with a CPI time series analysis, we get some idea on the major controls for the production of precipitation and the availability of water - the supply side of the water balance equation. On the demand side, a water budget model (Johnstone and Louie, 1984) is used to simulate runoff (precipitation - evaporation) consequently soil moisture, utilizing weekly mean temperature and total precipitation for inputs.

The situation for the water year ending September 1988, across Canada and northern United States is presented here.

2. Results

2.1 Trough/Ridge (Hovmoller) Diagram

Fig. 1a depicts the average features of the 50kpa general circulation patterns for the 30 to 50 degrees north latitude band spanning the northern hemisphere, from June to September 1988. For our purposes, we may trace the dash line (near 100 degrees longitude) running downwards, noting the stationary behaviour of a long wave ridge which have dominated North American dry spell through the end of June. This is consistent with the number of stations drying up in Fig 2. The ridging, which was sandwiched between an extensive cold Pacific trough (breaking down late June) and a narrower Atlantic teleconnection, started an east/west oscillation in late June. As general circulation controls resumed progression/retrogession movements, the CPI series (Fig 1b) showed at least 8 of the 12 stations monitored recovering from low winter precipitation effects.

The distances (in days) between ridge maxima approximate the 16-day planetary waves of the middle latitudes, and may help in anticipating major turns in dry/wet spells especially when considered in the light of group velocity pulses (solid line A-A is about 30 degrees longitude per day). At this speed, the propagation and dispersion of energy downstream is cycled around the globe in 12 days, just about the time constant conjectured for periodic moisture replenishment of the atmosphere. Short-term projections of these pulse lines (indicating speeds faster than individual waves), can be used for advanced timing of the excitation of surface weather systems (e.g. explosive developments, intensifications or severe weather), as mutual adjustments of wind and pressure fields take place.

2.2 Cumulative Precipitation Index

In Fig. 1b, the CPI (Strommen, et al, 1980; Mather, 1985) time series for a dozen Prairie stations is presented. This index represents a comparison of 8-week accumulations of total precipitation, to normal values for the same period. The cumulative period is extended beyond 8-weeks until the percentage ratio is above 60%. The 8-week accumulation interval is quite consistent with the time scale of the onset of agricultural drought as defined by Serafini and Sud (1987).

In general the CPI series portray low winter precipitation across the Prairies, with only Kenora, Saskatoon, and Kindersley benefitting from the usual spring showers. As the quasi-stationary Pacific trough broke down into shorter waves in late June, the ridging over North America responded with a late summer moisture recharge for 10 locations, but not much help for Moose Jaw and Lethbridge.

2.3 Water Budget Outputs

Time series of hydrologic components are compared with their respective normal values in Fig. 3. Overall, derived soil moisture series show very little recovery, except at Calgary and Edmonton. These places also peaked into the wet category (see Fig. 1b) during the summer months with a good share of convective storms. Yet, in terms of total water production only Edmonton marginally **exceeded** normal water requirements. None of the stations came close to normal winter precipitation.

These figures are quite self explanatory, and time series of hydrologic components can be produced for the 286 stations we monitor weekly across Canada and the northern United. States.

3. Concluding Remarks

The Prairie drought of 1988 was beset with low winter precipitation, very little of spring rains, and not much of a recovery from summer showers.

The monitoring and analysis system we have implemented at AES/CCC/CCAH can provide meaningful and comprehensive information to decision makers. The system integrates all available data from the ground up into atmospheric general circulation patterns, which in the future can easily accommodate general circulation model outputs.

Meanwhile, we hope to extend the water budget output time series by probabilistic-scenario-generating methods. Experiments in predicting temperature and precipitation trends as likely consequences of past events had been encouraging. The technique should tentatively fill the void in deterministic drought prediction.

4. Acknowledgements

Mr. Shig Ishida's programming of the CPI procedure, maintenance of ongoing database, and weekly updating of the indices are greatly appreciated. I thank Mr. A. A. Gergye of CCRM, for providing the Hovmoller diagrams.

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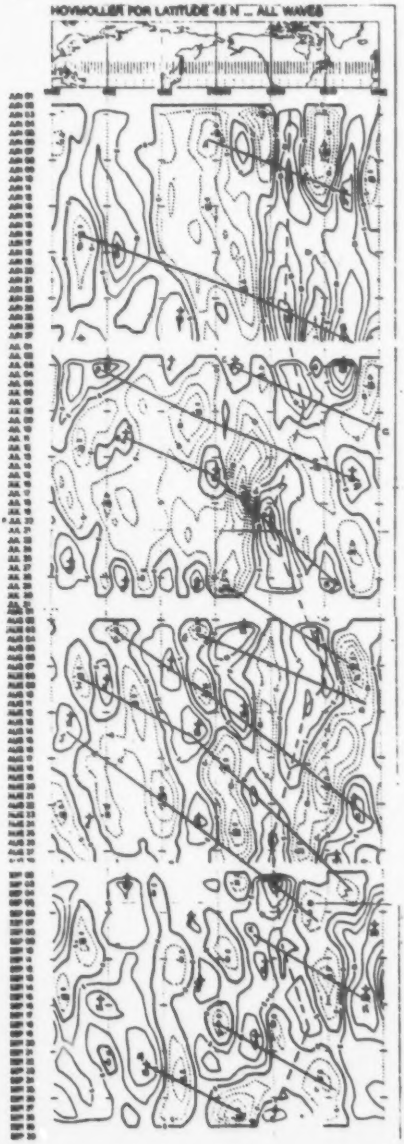
Fig. 1a Trough-ridge time section for latitude band 30-50 degrees north.



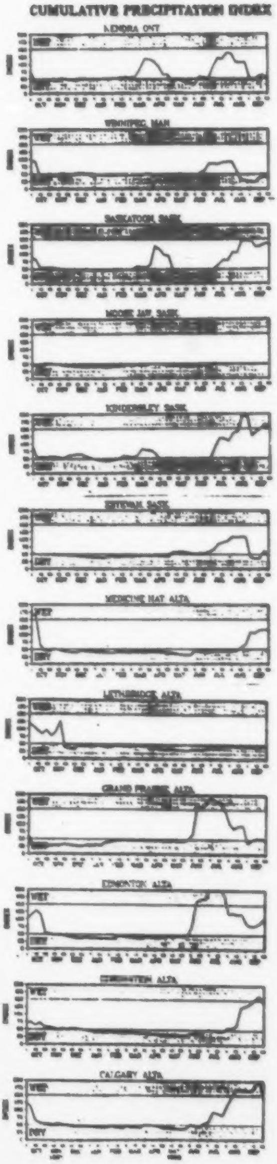


Fig. 1b Cumulative precipitation index time series from October 1987 to September 1988 at representative Prairie locations.

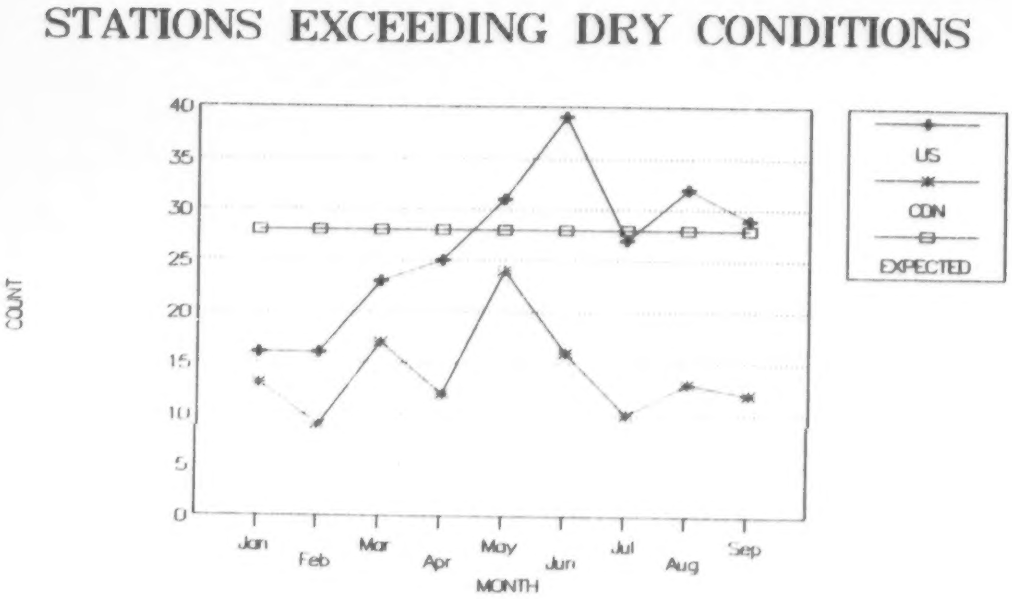


Fig. 2. Number of stations showing lower than 40% dryness.

CUMULATIVE PCPN INDEX
FOR 8 WEEKS ENDING
30 SEP 88

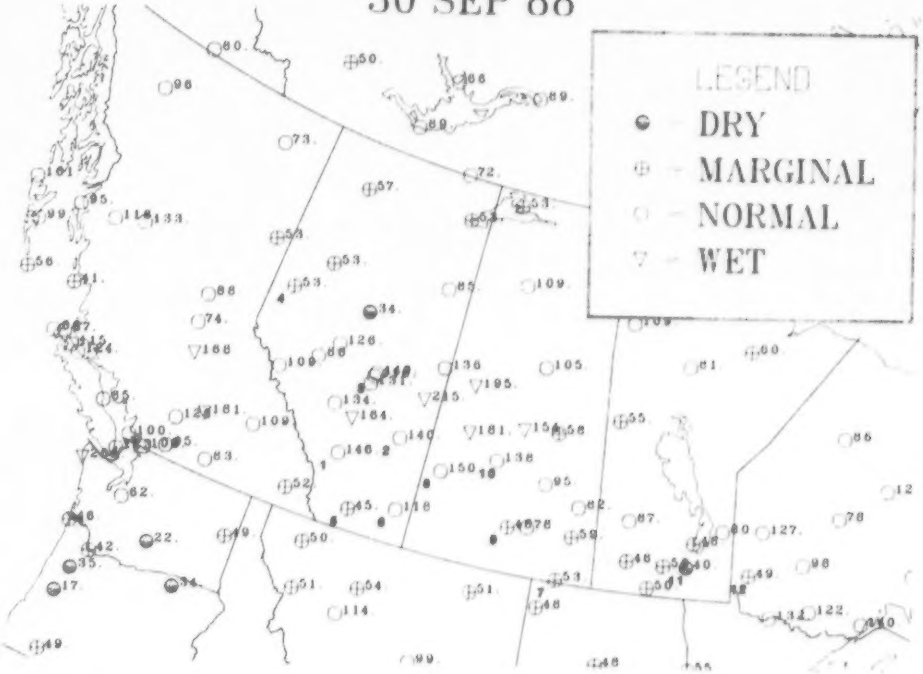

LEGEND
● – DRY
⊕ – MARGINAL
○ – NORMAL
▽ – WET

Figure 3

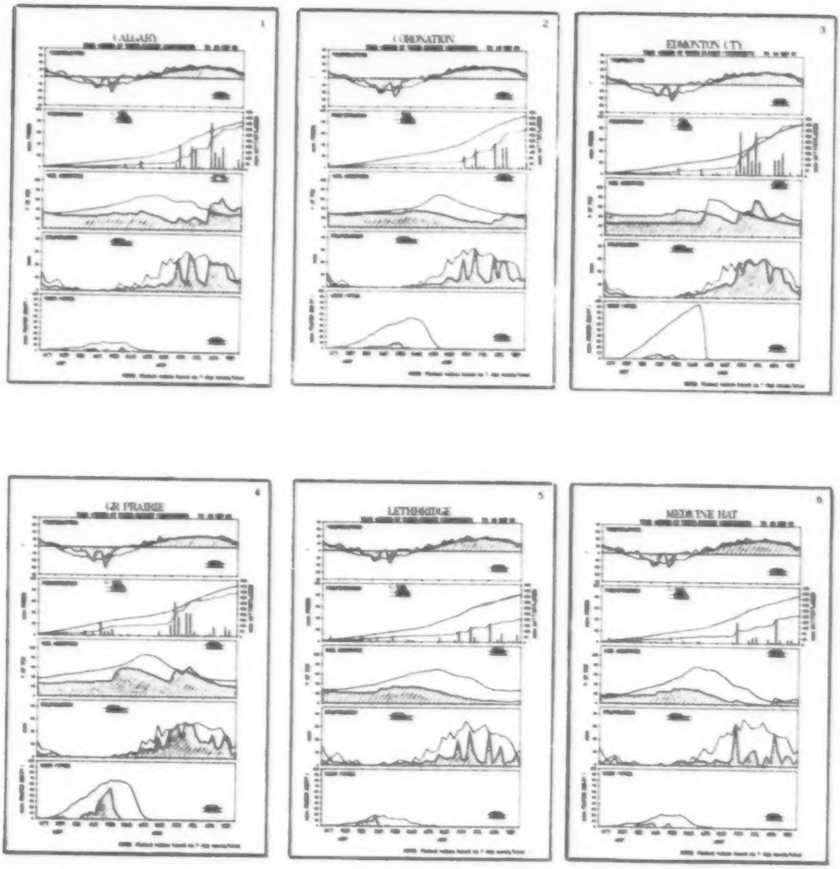


Figure 3a) Time Series of hydrologic components derived from water budget model.

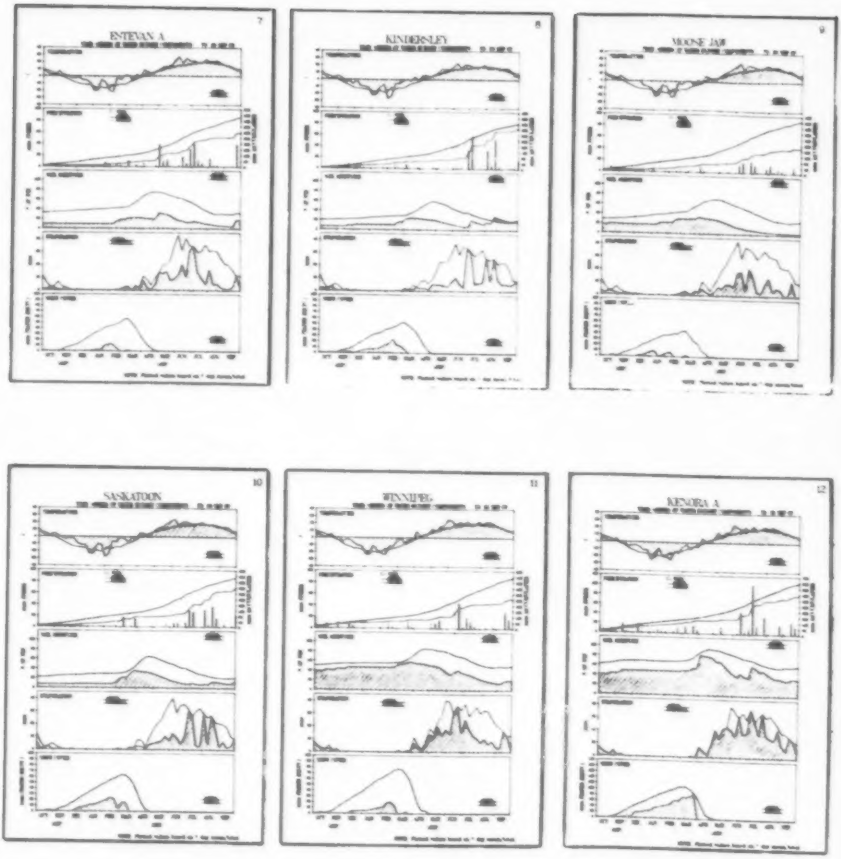


Figure 3b) Time series of hydrologic components derived from water budget model.

THE VARIABILITY OF VERTICALLY INTEGRATED MOISTURE FLUX DIVERGENCE OVER NORTH AMERICA

N. Sargent

INTRODUCTION

A large fraction of the water which enters or leaves the soil is carried to it or away from it by the atmosphere. A study of moisture fluxes and their divergence in the atmosphere allows an investigation into the causes of too much or too little moisture converging upon an area and affecting conditions at the surface. Such a study is essential if we are to understand how droughts form and break or if they could be prevented from occurring altogether. Datasets of global twice daily observations of the moisture content and velocity of the atmosphere are now reaching such a size that a systematic study of moisture fluxes, their divergence and variability is becoming possible.

Rasmusson (1968) and Peixóto and Oort (1983) have carried out studies of vertically integrated moisture fluxes and produced maps of flux divergence. They showed areas out of which the atmosphere carries more moisture than it carries in (positive moisture flux divergence -- evaporation exceeds precipitation) and vice-versa. Rasmusson had too few years of data available to consider the question of interannual variability of flux divergence. Peixóto and Oort mapped divergence on a global scale allowing minimal detail to be resolved over North America.

This study applies a similar technique to data from 1979-1987 to look in some more detail at the variability of moisture flux divergence over North America. Values found for the mean flux and its divergence compare well with those found by Rasmusson (1968) and Peixóto and Oort (1983). The RMS variance of annual mean flux divergence shows several separate and distinct areas of local maximum over North America. These maxima may result from year to year variations in the strength of relatively local processes responsible for flux divergence in those areas.

OBJECTIVES

The aim of this study is to gain an understanding of the atmospheric mechanisms behind interannual variability of large scale moistening and drying in North America. A long term objective is to evaluate the contribution to this variability of fluctuations in oceanic moisture sources, atmospheric jet strengths, large scale circulations and teleconnections.

METHOD

The method used is quite similar to that of Rasmusson (1968) and Peixóto and Oort (1983) and is detailed in Boer and Sargent (1985). Twice daily observations of wind and humidity at

10 levels from 10 to 100 kPa around the globe were available from the National Meterological Center (NMC) for the period Jan 1979 - Sep 1987. The minimum area resolvable in this data amounts to around 6×10^5 km^2. These analyses were projected onto a 3.75° x 3.75° grid. Moisture flux vectors at each level were composed at each time by multiplying the moisture content of the air at each point by its velocity. These were integrated vertically from the earth's surface to the top of the atmosphere to give vertically integrated moisture fluxes. They were then accumulated into monthly average fluxes and their divergences were computed.

Where moisture flux diverges then more moisture is flowing out of the region than into it. This can only result from a depletion of the moisture content of the atmosphere/surface (soil, ocean) system. Rates of change in the moisture content of the atmosphere over the annual cycle rarely exceed a small fraction of a mm of water per day so they are ignored in the results presented here. All the remaining moisture flux divergence represents loss of water from the surface. A similar line of reasoning shows that moisture flux convergence represents net deposition of water at the surface.

RESULTS

An overall picture of mean conditions is given by the grand average maps for each season shown in Fig. 1. The flux vectors form a coherent field running broadly from west to east across the continent. Areas of significant flux convergence and divergence occur on smaller scales than obvious changes in the flux itself, down to the smallest resolvable in the data. This suggests that the immediate causes of dry and wet portions of the annual cycle are relatively local conditions influencing deposition and absorption of moisture by the atmosphere in the affected areas and not variations in the large scale strength of the atmospheric moisture jets or their distant sources.

The main features of the divergence field in winter are strong flux convergence over the northwestern Pacific coast and divergence over the east coast. Strong divergence appears offshore from the southwest coast and over the Texas gulf coast in summer months. Inland there are centres of flux convergence in the lower midwest in spring and summer moving east and north toward the great lakes in fall and winter. A secondary maximum of convergence also appears over northern Saskatchewan in fall and winter. A similar area also occurs over northern Nevada in summer replaced by an area of divergence over Utah in winter. Most of these features are also visible in Rasmusson (1968) and Peixóto and Oort's (1983) maps.

These features all appear on the map of annual mean moisture flux and divergence for the period 1979-1986 which is shown in Fig. 2. Also shown (Fig. 3) is a map of the RMS variance of annual mean moisture flux divergences for each of the years 1979-1986 about the mean for that period. Regions of high moisture flux divergence variability occur along the coasts, in the central midwest, and over northern Saskatchewan. These centres appear to be associated with areas of divergence extrema in the same regions which were identified above.

CONCLUSIONS

Preliminary results of this study indicate that annual mean vertically integrated moisture flux divergence over North America is determined by processes on synoptic or smaller scales occurring independently in different areas and times of the year. Variations in the strength of any of these processes in one year may lead to local anomalies in moisture flux divergence for that year. More work is required to identify these processes and determine their mechanisms.

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Figure Captions

Fig. 1 Mean moisture flux (arrows) and its divergence (contours) for Dec-Jan-Feb (a), Mar-Apr-May (b), Jun-Jul-Aug (c) and Sep-Oct-Nov (d). The divergence is expressed in mm/day with a contour interval of 1 mm/day. Areas with flux convergence exceeding 2 mm/day (moist) are stippled and those with divergence exceeding 2 mm/day (dry) are hatched. The box in the lower right shows the length of arrow representing 200 kg/(m sec) of moisture flux.

Fig. 2 As in Fig. 1 but for the annual mean over the period 1979-1986.

Fig. 3 The RMS variance of the individual yearly mean maps of flux divergence about the mean shown in Fig. 2. The contour interval is 0.2 mm/day. Areas with a variability of between 0.4 and 0.8 mm/day (14.6 and 29.2 cm/yr) are stippled, those with a variability of between 0.8 and 1.2 mm/day (29.2 and 43.8 cm/yr) are hatched horizontally and those with variability greater than 1.2 mm/day (43.8 cm/yr) are hatched vertically. Note the local maxima off the coasts, in the central plains and in Saskatchewan.

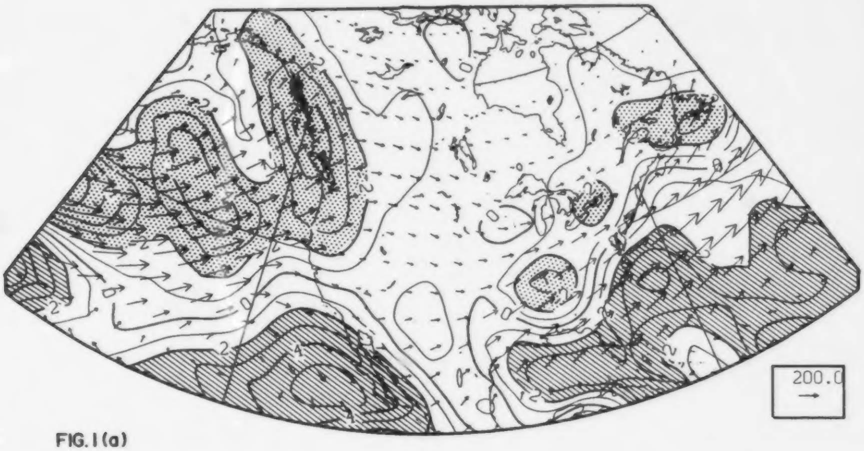

FIG. 1(a)

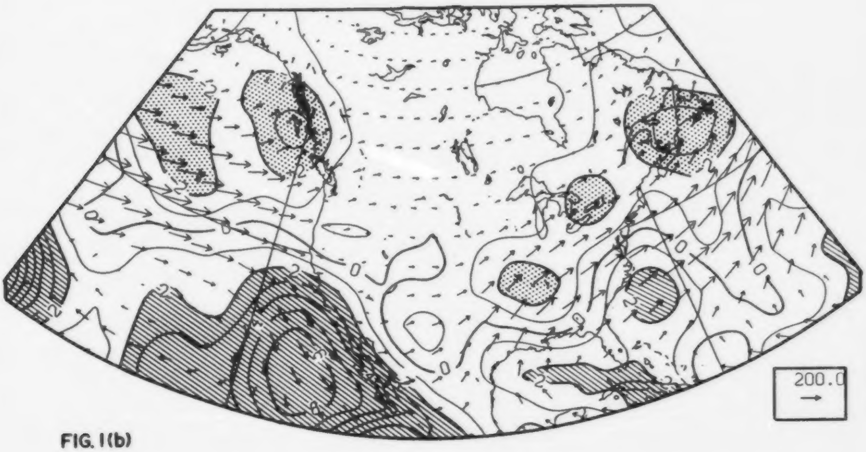

FIG. 1(b)

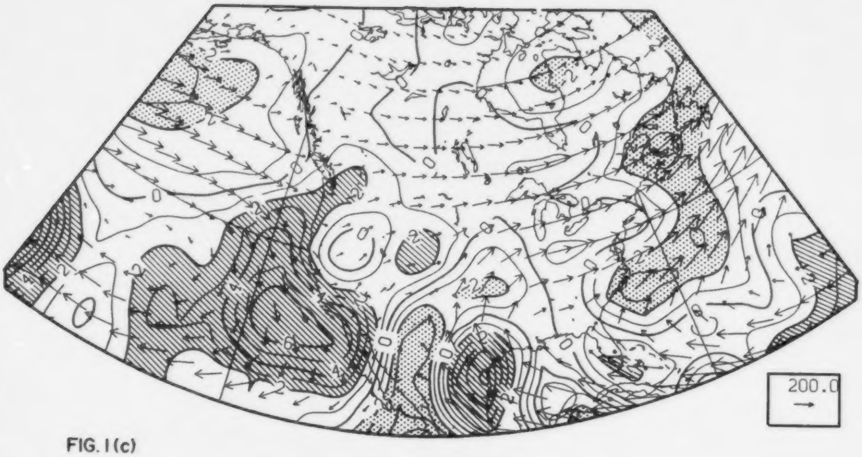

FIG. 1(c)

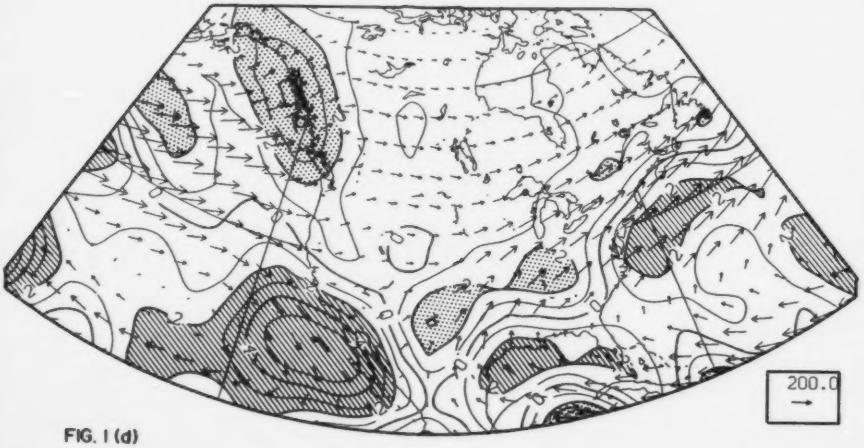

FIG. 1(d)

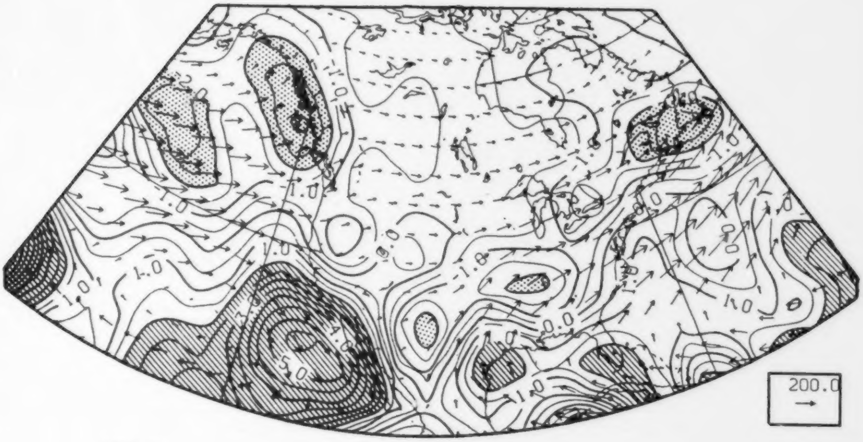
1.0
4.0
5.0
2.0
0.0
200.0

FIG. 2

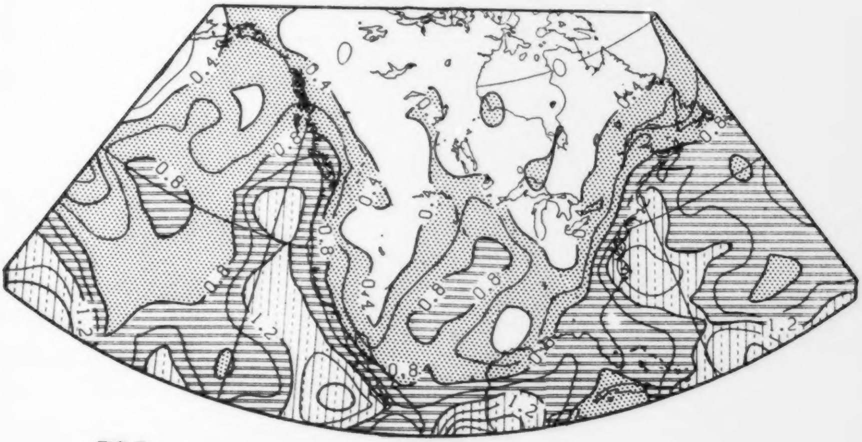

FIG. 3

A CANADIAN AGRICULTURE WEATHER MONITORING (CAWM) SYSTEM

J.A. DYER

AGRICULTURE DEVELOPMENT BRANCH
AGRICULTURE CANADA

INTRODUCTION

This poster paper describes a new weather based crop monitoring package which has been run on a pilot basis during the 1988 growing season. The system, known as CAWM, for Canadian Agriculture Weather Monitoring, provides a variety of crop growth indices across Canada. These indices can be both normalized and projected into the future, allowing users to relate to past conditions and to assess their expectations at the end of the current growing season. Flexibility was another key guideline in CAWM. Revisions to historical reference estimates can be easily made to match the changing requirements of current crop weather analysis.

THE SYSTEM

The flow chart shows the operational steps in the CAWM System. Operations start with data acquisition software written by OceanRoutes Canada, under contract to Agriculture Canada, which resides on the OceanRoutes International computer. The task of this software is to retrieve synoptic weather data from weather archives immediately after the weather forecasters have finished using them. These data are re-organized into daily records and an estimate of daily evapotranspiration potential is added.

These data are transmitted from the OceanRoutes Weather Data Base to Ottawa over the TYMNET telecommunication system (formerly DATAPAC). Blocks of data consisting of individual records for all stations in one day, are received on a PC-XT personal computer. D-base is used to sort these data into station files. Another step prior to the actual data analysis is required. Overwriting, a function borrowed from FoDEWS (Dyer et al, 1982), provides a way of substituting proxy data for both missing observations and future weather periods. Following overwrite (see Figure 1) these data are suitable for a generating variety of crop weather indices.

DATA SOURCE

Synoptic weather observations from 140 first order weather stations across Canada provide the source data. Four observations per day of temperature, radiation, precipitation and wind run are received from each weather station prior to the analysis described above. The synoptic data are prone to missing records, due to the weather forecasting requirement for rapid acquisition and analysis. Agricultural monitoring is a secondary use and the time and effort required to backfill for late reported observations or substitute data from nearby stations is a major limitation.

Substitution of climatological normal values for each missing day tends to bias estimates towards normal conditions when there is a high percent of missing data. This substitution is done automatically for all missing records. Failure to report all observations immediately from the weather stations results in approximately fifteen per cent missing precipitation and seven per cent missing temperature values. Therefore the analytical results should be used as an overview, against which regional or provincial reports can be compared. They should be considered as reconnaissance information and interpreted with some caution, given the limited spatial coverage and the missing observations.

AGRICULTURE WEATHER INDICES

The crop weather indices which can be derived from CAWM range from simple accumulations over periods of time to complex crop water use and soil moisture simulations. To date the following information is generated from CAWM.

Indices:- Cumulative Crop Water Use (or Actual Evapotranspiration)
- Soil Moisture Reserves (% of Maximum Storage)
- Cumulative Precipitation
- Cumulative Heat Units (Degree Days Above 0.0°C; above 5.0°C)
- Cumulative Corn Heat Units (Chapman and Brown, 1966)

NORMALIZING

All of the above indices can be presented in normalized form (current estimates as a % of historical average). Historical reference data include the published AES climate normals (AES 1982a and b) for 1951 to 1980. A special procedure developed for CAWM generates proxy daily records from monthly normals. Proxy daily normals allow the above cumulative indices to represent any desired integration period. These same proxy daily records are the basis for overwriting, where cumulative periods can be projected to future dates.

SIMULATION

The first two of the above indices depend on a computer simulation model. Version III of the versatile soil moisture budget (Dyer and Mack, 1984a) generates both soil moisture estimates and crop water use accumulations for any specified period (see S.M. and AE model in Figure 1). Daily crop water use is estimated from the change in soil moisture due to root extraction. To derive realistic soil moisture estimates from the proxy daily records, three proxy years are used in the overwrite procedure. This allows for artificially scheduled precipitation events to be staggered. In contrast, only one year of proxy data is required if no simulations are required because daily rainfall sequences are only important in the soil moisture simulations.

Crop water use (or actual evapotranspiration) over the growing season is an indication of vegetative growth rates, since transpiration, the consumption of water by plants, and photosynthesis, the production of plant tissue, are closely related (Dyer, 1987). Since crop yields are highly dependent on biomass density, general crop yield expectations are reflected in the crop water use figures. For field crops and for forages, the per cent of normal crop water use figures can also be taken as per cent of normal estimates of crop yields.

Multiplication of each figure by the regional long-term average crop yield for various crops gives a current yield estimate. It must be noted that such estimates are based solely on crop water supply with many other factors being ignored. Conditions such as frost or heat stress, which affect both grain filling and germination, or excess rainfall, which interferes with harvesting, are not taken into account. Future plans call for such indices being added to CAWM.

PRESENTATION & REPORTING

The system is oriented toward reconnaissance. The basic means of presenting analysis results is a national map, computer drawn in a convenient page size format. Results are summarized in a set of 27 geographic regions. A regional value consists of the average of all sites assigned to that region. A master station list provides regional assignment codes for all 140 sites. A value is printed on the map for each region depending on the crop condition index being analysed. Several example maps are displayed here.

The geographic reporting regions are numbered and named according to the main physiographic or natural features (e.g., rivers, cities, provincial boundaries). The reporting regions were designated on the basis of weather station locations and geographic similarity. The following table and map defines the names and approximate locations of the regions.

APPLICATIONS

The target audience is primarily government decision making heads. Such managers often have only limited access to objective and accurate regional information on a day to day basis. A need for a national overview of weather based crop growing conditions was especially apparent during 1988. There were severe periods of drought in both British Columbia and Ontario that were comparable to the drought in the Prairie Provinces, when considered in normalized terms.

The reconnaissance nature of CAWM can play a key role in mobilizing more intensive and cross-disciplinary information gathering efforts by identifying the early symptoms of drought and other weather related problems. CAWM can also play this overview role in the private sector by indicating the potential flow of farm products to market. Crop weather monitoring, such as provided by CAWM, could also make a direct contribution to many types of farm management (Dyer and Mack, 1984b). Reports and maps from CAWM have been released on an experimental basis to the agricultural industry via the PULSE REPORT and the FRUIT and VEGETABLE REPORT (both published by the A.D. Branch of Agriculture Canada).

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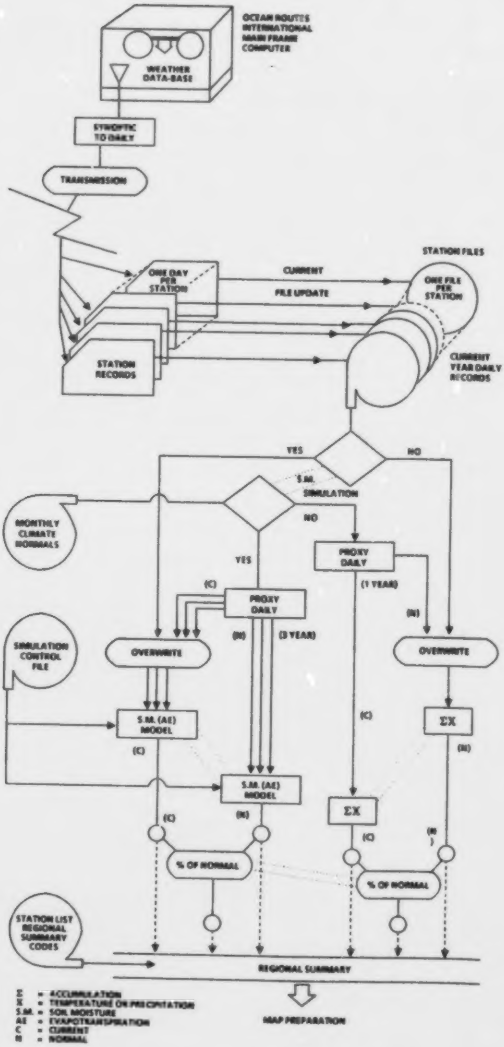
ACKOWLEDGEMENTS

Dan Cianferro and Randy Muma are gratefully acknowledged for their contributions to the computer programming and data management aspect of CAWM. Both contributed greatly to the overall operational success of the CAWM system. Susan Lally of OceanRoutes Canada is also gratefully acknowledged for her guidance and work in establishing the OceanRoutes data base for agriculture use in Canada.


OCEAN ROUTES INTERNATIONAL MAIN FRAME COMPUTER
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ONE DAY PER STATION
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ONE FILE PER STATION
STATION RECORDS
CURRENT YEAR DAILY RECORDS
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NO
S.M. SIMULATION
MONTHLY CLIMATE NORMALS
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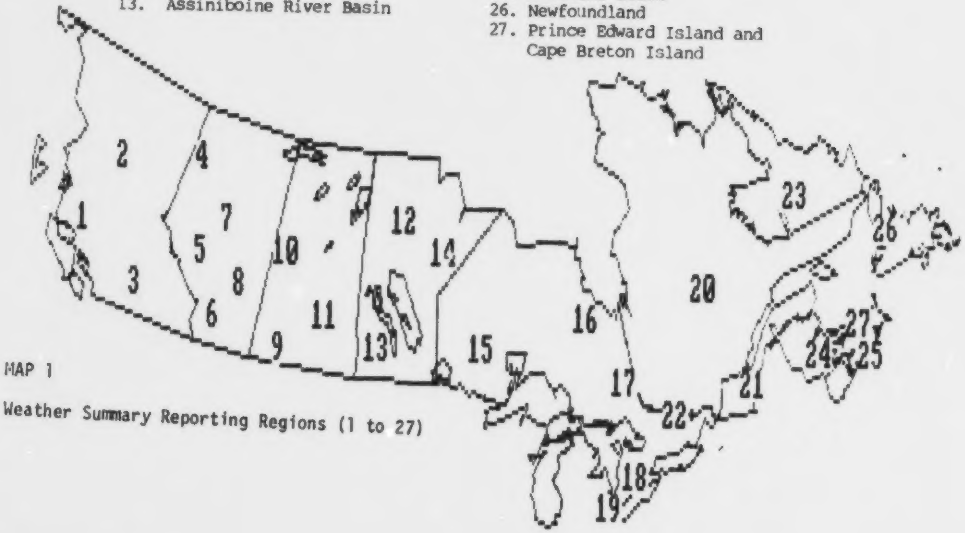
% OF NORMAL
% OF NORMAL
STATION LIST REGIONAL SUMMARY CODES
REGIONAL SUMMARY
MAP PREPARATION
Σ = ACCUMULATION
X = TEMPERATURE OR PRECIPITATION
S.M. = SOIL MOISTURE
AE = EVAPOTRANSPIRATION
C = CURRENT
N = NORMAL

FLOWCHART OF THE CAWM SYSTEM.

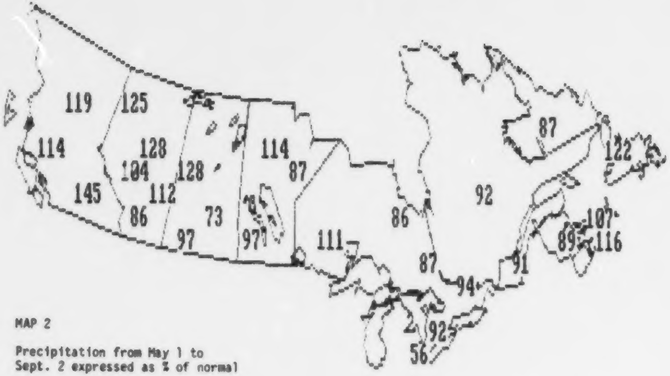
WEATHER SUMMARY REPORTING REGIONS

1. West Coast
2. North Central British Columbia
3. Central British Columbia
4. Peace River Basin
5. Rocky Mountain Foothills
6. Southern Alberta
7. Central Eastern Alberta
8. Coronation
9. South Western Saskatchewan
10. Western Saskatchewan
11. Regina
12. North Central Prairies
13. Assiniboine River Basin
14. Severn River Basin
15. Kenora
16. Hudson Bay Basin
17. Central Ontario
18. Southern Ontario
19. Windsor
20. Laurentian
21. St. Lawrence Lowlands
22. Rideau-Gatineau
23. Labrador
24. Appalachian
25. Maritime South
26. Newfoundland
27. Prince Edward Island and Cape Breton Island



MAP 1

Weather Summary Reporting Regions (1 to 27)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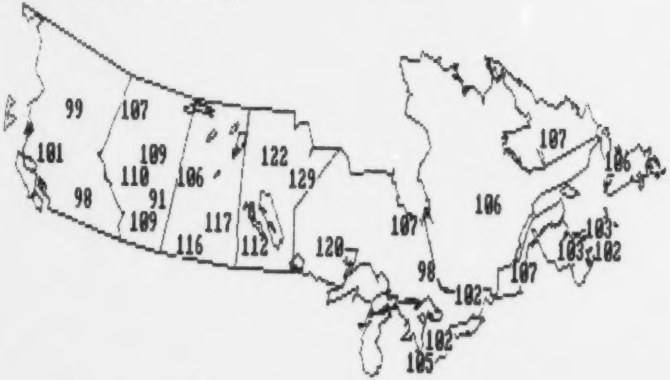
MAP 2

Precipitation from May 1 to
Sept. 2 expressed as % of normal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MAP 3

Degree Days above 5°C from May 1 to
Sept. 2 expressed as % of normal

A PREHISTORIC RECORD OF DROUGHT IN SOUTHERN ALBERTA

If we are to expand on the rather limited record of historic drought events on the Canadian prairies and arrive at a better understanding of long-term climatic dynamics, it is necessary to consult proxy records of climate change. Among the most frequently utilized proxy records of past climate are pollen and plant macrofossil stratigraphies. We have initiated a study in southern Alberta that utilizes these indicators of past environmental change. Our goals include documenting the frequency of prehistoric drought periods in the region and assessing the severity of these major drought events.

Chappice Lake lies some 50 km northeast of Medicine Hat. It was chosen for study because, a) it has little surface inflow and outflow, thus the lake's water level is controlled mainly by precipitation and evaporation in its drainage basin, b) coring and radiocarbon dating revealed the lake is long-lived (about 4000 years) and that sediments have been deposited rapidly, indicating that relatively short-term changes in water levels may be detected and, c) it has not been affected by irrigation practices.

Laminations in the lake sediment point to past water level fluctuations, since these features were most likely formed by precipitation of minerals and by biological activity as brine chemistry changed. Laminations formed during low water phases may be detected by an abundance of *Ruppia* (widgeon grass) pollen and seeds contained within them, since this aquatic plant is known to thrive in water of high salinity. Periods of recharge may be discerned from high Chenopodiaceae (goosefoot) seed input (as seeds were washed into the lake from its margin during recharge) and declining *Ruppia* pollen and seed representation.

Combining these interpretations (and others) of the fossil record with accelerator mass spectrometry radiocarbon dating has allowed us to construct a preliminary chronology of paleohydrological events.

To date, about half of the Chappice Lake core (repesenting about 2000 years of sedimentation) has been analyzed. Preliminary results indicate two major periods of heightened drought frequency occurred between approximately AD 850 to 1350 and AD 1675 to 1900. These drought periods fall within the Medieval Warm Period and the latter stages of the Little Ice Age, respectively. Since these historic climatic phases are thought to have been produced by changing patterns of the circumpolar vortex, we suggest periods of frequent high pressure blocks may have been responsible for many of the most severe past drought periods on the southern Canadian prairies during the late Holocene.

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EVALUATION OF CROP INSURANCE, STATISTICS CANADA (CROP SURVEY) AND WEATHER BASED ESTIMATES FOR ASSESSING WHEAT YIELDS IN SASKATCHEWAN

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INTRODUCTION

Accurate estimates on the production of cereal crops are important not only for efficient marketing of these crops but also for assessing the impact of farm management practices under different weather and climatic conditions. Total production of spring wheat in Canada may increase as much as 40% over a three-year period as it did from 1984 to 1986 (18.06 million tonnes to 25.4 million tonnes) and decrease a year later by 18% (21.02 million tonnes). Wide differences exist also in yield and in production within a crop district for different crop management practices within a soil climatic zone. In the Brown Soil Climatic Zone having a total soil water deficit of 400 mm during the crop year, fertilizer response is negligible in most years even when the crop is seeded on summerfallowed land. In the Black Zone where the soil normal moisture deficit may be under 200 mm of water, the fertilizer response is considerable on both stubble and fallow cropped land.

For marketing purposes, the first report of a change in the production supply from the previous year comes in the spring with the publication by Statistics Canada of the seeded acreage intentions based on a farm survey made in March. This is followed in July by a survey of acreage seeded by June 1. No further adjustments are made in acreage estimates from changes in seeded lands after June 1. The next indication of the production comes with the early harvest yield survey made in August. Subsequent updates of the production and yield estimates are made in the following months based on farm yield and total production surveys. Final yield estimates are based on total production divided by the total acreage. The estimates are based on surveys made for fourty-five crop districts in the three prairie provinces to provide the provincial estimates. Special reports are made in January on the yield for the previous year from the two major crop management practices: i.e. grain harvested from crop seeded on land summerfallowed the previous year and from grain harvested from land previously cropped. No information is available on response to fertilization in the different soil climatic zones. These yields are simple averages from crop reporters who harvested wheat both from the fallow and stubble land. By focusing on these crop reporters, the underlying management philosophy is similar for both stubble or fallow land.

This relatively simple approach when combined with the update from the Census Survey data every five years generally provides satisfactory long-term information on trends in production over time. However, little information is available from these reports for agencies requiring information on the impact of various management practices (crop rotation, fertilization tillage) for soil conservation studies or for assessment of the impact of a particular weather situation on crop production. Furthermore, the relative acreage subjected to specific cultural practices varies among the zones and over years within the zones. The regular crop district yields published by Statistics Canada are weighted by the relative acreage of the dominant management practice. Thus, production and yield estimates for a crop district would be affected by a change in the relative acreages for the different management practices. Consequently, when using this data set, information is not available for accurately analyzing the relative impact of the individual management practices on yields. Thus, for studying impact of soil conservation studies or of a change in weather conditions on crop growth other data sources are required.

A second source of yield, acreage, and production values is being acquired by provincial Crop Insurance agencies. Since the inauguration of crop insurance coverage by most provinces in the last decade or two, historical files of yield records from individual producers have been collected. This data source is associated with management and cultural practices under actual farming conditions. These data have been accumulating for different crop types, varieties, cultural practices, and chemical applications, etc. Confidentiality of individual producers is maintained by integrating the individual field records into stratified sub-sets. These data are useful for analyzing impact of selected management practices and of weather on yields of major cereal and oilseed crops. For example, yields would be available for cereal crops grown on fallow and on stubble-crop lands, fertilized and unfertilized, with associated acreages since 1960 in Manitoba and since 1973 in Saskatchewan and Alberta. Specialized crops have been added at various times in recent years. These data are not readily available. They are provided by the Crop Insurance agencies only on special request and there is a delay of six months to a year after the latest production year. For acreage estimates they may not represent a valid sampling of different management practices as they represent data only from farms under the insurance plan. Thus, acreages of some practices conceivably might not be representative of the area.

A third source of information for assessing the impact of weather on current crop production has been estimates provided annually for each of the crop districts in the prairies for several years by the Agrometeorology Section, LRRC, (Mack, 1980-86). These estimates are based on the relationship between crop growth response (yield) and weather-soil relationships which occurred from 1961 to 1978. The relationships were developed from research conducted during the 1960's using meteorological data for assessing impact of weather. In 1968 Mack and Ferguson published a Moisture Stress Index for estimating yield of wheat. They showed that an Index calculated from the shortage of water for evapotranspiration was directly related ($R^2=0.83$) to the decrease in yield. Yield was more highly correlated to this Index than to total precipitation ($r^2=0.62$) or to the ratio of AE/PE ($r=0.59$) over a 9-year period. Williams (1965 and 1973) identified several parameters to quantify soil moisture stress under Canadian prairie conditions: conserved precipitation prior to seeding, May and July potential evapotranspiration, June water deficit, Seasonal Deficit to July 31, and the interaction between Seasonal Deficit and soil texture. In a stepwise selection of dominant weather factors affecting yield, the Seasonal Water Deficit and the June deficit components most frequently reduced the yield whereas the potential evapotranspiration in May frequently increased the yield. These studies were based on the yield data available at that time from Statistics Canada (i.e., acreage weighted mean yields for a crop district) (Williams et al., 1965, Williams, 1973). These weather-based estimates do not consider direct effects of damage from a localized invasion of insects or disease in a specific year.

Saskatchewan was selected for an evaluation of the yield data from the three sources as it is the dominant producer of spring wheat in Canada. From 1983 to 1986, the Saskatchewan production of hard red spring wheat was 55.7% of the total average Canadian production of 21.66 million tonnes. This wheat production was grown on 59.6% of the total acreage seeded to wheat of 11.41 million hectares. The production of wheat in Saskatchewan is grown mainly in three soil climatic zones. The climate of these zones has effected major differences in the farm management practices. The dominant climatic factors have been the temperture regime and availability of soil water for plant growth to meet the wide range in transpiration across the three zones. These factors result in large differences in growth development plant density and plant water stress. Consequently, these climatic factors impact on management practices and must be considered when making agronomic, crop management and economic analyses of the prairies.

An understanding of the limitation of various crop data sources and their relative biases can contribute to a better understanding as to which source should be used for a particular purpose. In this paper, the relationship of three data sets obtained from three distinctly different sources are evaluated. The objective is to determine if these data sets can be used for cross calibration when one data set becomes unavailable and, also, whether yields and production, when estimated from weather on a timely operational basis during the growing season, compares favorably to that of the other two data sources which are not available until well after harvest operations.

DATA SOURCES AND ANALYTICAL PROCEDURES FOR THE EVALUATION

(a) Statistics Canada

From 1981 to 1986, the Crops Section published for the prairies the acreage of spring wheat seeded in each Crop District. In addition, they published a breakdown of the yield of spring wheat grown on fallow and on stubbleland (Statistics Canada, Field Crop Reports 1981-86 Vols. 60-65). Unfortunately, these data still mask the impact of other management factors (e.g. fertilization practices). These yield data represent, a combination of yields from both fertilized and unfertilized cropland. The proportion of the crop fertilized, however, differs for fallow and stubble-land within each of the major soil-climatic zones in Saskatchewan. This may also vary among years within each zone. As Statistics Canada estimates for spring wheat and for all-what which includes Durum and winter wheat are based on field observations and updated as harvested estimates become available, they usually include the influences from both local weather and biophysical damage (viz. spring flooding disease and insects).

The total acreage that is seeded by June 1 in a crop district is published in September of the harvest year and is not adjusted for subsequent changes after June 1. The crop district yield data are not available usually until January following the harvest year. The accuracy of the production estimates depend on the accuracy of both the yield and the acreage estimates.

(b) Crop Insurance Data

Data on yields of spring wheat for Saskatchewan have been recorded by the Saskatchewan Crop Insurance Corporation since 1973. The individual field records for spring wheat from 1980 to 1985 were combined for this study into four data sets of a 2x2 combination of crop seeded on fallow and stubbleland and with and without fertilizer application. The yields and acreages which are recorded on an individual field basis were combined into one of the four subsets and aggregated annually on a Township and on a Crop District basis for each of the twenty Crop Districts (C.D.'s) in Saskatchewan. The yields of the four sub-sets for a crop district were given a quality control assessment based on: (a) their "relative yield" values; and, (b) the acreage (sample size) associated with each yield value. Results of agronomic studies on crop rotations in the prairies show that yields of all cereal and oilseed crops have a consistent "relative relationship" between fertilized and unfertilized crops seeded on fallow and stubbleland for similar soil textural classes, weather conditions, and soil moisture deficit situation. In general, yields of crops grown under the following management practices have the following 'relative yield relationships': Fallow crop ≥ Stubble Crops; and Fertilized crops ≥ Unfertilized crops grown under a similar rotation. Yields for the four sub-sets were assessed acceptable if they met the 'relative relationship' rule within error limits and were derived from > 200 hectares. Usually yields which did not meet the 'relative relationship' rule were derived from an aggregation of acreages that constituted a sampling size of < 400 hectares. Such a small sample size usually represented a management practice minimally used in that Climatic zone (e.g. Fertilized stubble cropland in the Brown Soil Zone or Unfertilized fallowland in the Black Soil Zone).

(c) Weather-based Yield Estimates

Yield estimates were made for "all-wheat" which includes spring wheat, Durum, winter wheat from 1979 to 1986 for twenty Crop Districts in Saskatchewan. These estimates were based on the relationship of Statistics Canada Crop District yields. Before making the yield estimate, weather data for each crop district was generated from the station data using the Thiessen polygon procedure (Thiessen, 1911; Williams and Hayhoe, 1982). The "all-wheat" yield file (Statistics Canada) was used as over 80% of the wheat grown in Saskatchewan is spring hard red wheat. The "all-wheat" yield estimates were made using two sets of relationships. The first set was used for the period 1979 to 1982 based on the relationship (designated as 36-18) which was developed between 42 crop district yields and weather data from 36 climate stations covering all of Western Canada data using data for 1969 to 1978. The yield estimates used daily weather observations from 18 stations in Saskatchewan.

The annual "all-wheat" yield estimates for the second period, 1983 to 1986, were based on the relationship (designated as 131-30) which was developed between 42 crop district yields and 131 climate station data covering all of Western Canada for the period from 1961 to 1978. The annual yield estimates for 1983 to 1986 were made using weather observations from 30 stations in Saskatchewan (Mack, 1980 to 1986). In 1987 and 1988 yield and production estimates were made for spring wheat only. These estimates were based on a multiple regression using Saskatchewan Crop Insurance records for spring wheat from 1973 to 1985 for each of the 20 crop reporting districts in Saskatchewan. Separate regression coefficients were calculated for crop estimates on fallow and on stubbleland.

For both the 1983-1986 and the 1973 and 1985 relationships, the yield estimates are calculated for each of two management practices: crop seeded on fallowland and for crop seeded on stubbleland repesenting two different levels of soil water reserves at seeding time. A 10-variable multiple regression equation was used which included the following weather-related parameters on a crop district basis: (1) conserved precipitation prior to May 1, (2) linear technology trend; (3) potential evapotranspiration in May and in July, (4) moisture deficit in June, i.e. the shortfall in precipitation in June to meet evapotranspiration requirements in June; and (5) Seasonal Deficit, i.e., the overall seasonal shortfall of conserved precipitation for the 21 or the 8-month period prior to seeding plus the summer precipitation from May 1 to July 31 in meeting the evapotranspiration requirements of the crop (May 1 to July 31). The impact of the Seasonal Deficit on crop yields was analyzed in reference to Crop Insurance and Statistics Canada yields. In general, weather-based estimates primarily reflect the direct impact of weather and long-term normal biophysical effects on yield but they do not include the extraneous non-direct effects on yield such as insect or disease damage that may occur for a particular year.

The yield estimates for fallow seeded crops include conserved precipitation (CP) from August 31 of the previous crop year through the summerfallow year until May 1 of the present crop year (21-month conserved precipitation period). However, the estimated yields for stubble-seeded crops include conserved precipitation only from August 31 of the previous year to May 1 (8-month conserved precipitation period).

For a given year, a standard deviation was calculated from the yields of the crop districts to provide an estimate of the range in the crop district yields for that year in the province.

RESULTS OF THE ANALYSES

(a) Effect of Management Practices on Yield Within Crop Districts

An illustration of the wide differences in wheat yields within a crop district for each of the four main management practices (fallow, stubble; fertilized and unfertilized) is presented from the Crop Insurance Data source (Table 1). One crop district in each of the three main Soil Climatic Zone is presented. The mean of the four management values representing the crop district value is included. The standard deviation (S.D.$\bar{y}$) shows the large variation associated with the mean yield due to the management practices. For 1985, these S.D. values for CD #4A were 135 kg/ha for a mean yield of 370 and for CD #9B the S.D. was 726 for a mean yield of 1668 kg/ha. Different mean yields for a CD may vary also depending on whether they are calculated from the arithmetic mean of the four management yields (as previously calculated) or calculated from a weighting based on the relative acreage for each management practices. For example, for CD #4A and #9A for 1985, the weighted mean yields were 365 and 2125 kg/ha respectively as compared to previous values of 370 and 1668 kg/ha. The relative distribution of acreage for the four practices reflects the dominant practices used for wheat production within each of the crop districts and climatic zones. In the Brown and the Dark Brown Zones where the long term Seasonal Water Deficit (May to September, 50% probability) is normally over 400 mm and 300 mm, respectively, (Agroclimatic Atlas of Canada) the dominant practice for producing wheat is the cropping of unfertilized fallowland. In the Black Soil Zone where the Seasonal Water Deficit is normally between 200 and 300 mm, the dominant practice is the cropping of fertilized stubbleland. The low yield response to fertilizer on fallow in the Brown soil zone for these years (e.g. CD #4A, 1982: < 336 kg/ha) confirms the limited use and the long term agronomic recommendations of this practice. This low response is in contrast to the larger response to fertilizer for wheat grown on stubbleland (> 672 kg/ha: 1982, 1983 and 1985 for CD #9B) for the Black Zone and supports the popular use and recommendations for fertilizing stubbleland for this Zone.

(b) Comparison of the Three Data Sources for Provincial Estimates

Provincial yield values derived from each of the three data sources are compared in Table 2. Yield of wheat grown on fertilized fallowland was the cultural practice selected from the Crop Insurance data file. Yield for wheat grown on fallowland reported by Statistics Canada was most comparable. The Statistics Canada data set represents simple average yields of fallow field from crop reporters who harvested wheat from fertilized and unfertilized fields. Only farms which grew wheat on both fallow and stubbleland are included by Statistics Canada in compiling the reported values. The provincial values were calculated from a data set of crop district values for each data source. A correlation was calculated between the corresponding crop district values for each year. A correlation between the two sets is high ($r = > 0.88$) for each of the six comparable years. The regression and intercept coefficients are included to assist in adjusting the crop district values of one set to the other. The relationship between the two sets was lower in 1982 when yields were high for all crop districts than for years when growing conditions were poor for some of the crop districts in the province. The Weather-based estimates, calculated in July of each crop year, were highly correlated with Statistics Canada estimates ($r = > 0.88$) from 1983 to 1986, when data from 30 weather stations were available under special arrangement from Atmospheric Environment Service. The correlations of the crop district values were lower during the previous period from 1979 to 1982 when only 18 weather stations were used for the estimates.

(c) Comparison of the Three Data Sources for Crop District Estimates

1. Comparison of Crop Insurance and Statistics Canada Estimates

A comparison of the crop district yields for fertilized and unfertilized crops grown on fallow and stubbleland in relation to Statistics Canada fallow and stubble yields are illustrated for two years - 1984 and 1985 in Figure 1. This figure shows the distribution of crop district values for crop insurance relative to the values for Statistics Canada. The Crop Insurance crop district yields for unfertilized fallow and stubbleland are lower than for the fallowland yields from Statistics Canada. This association is reasonable as the values by Statistics Canada for fallow represent yields from fertilized and unfertilized lands. The Crop Insurance yields from fertilized lands are higher than the yields from Statistics Canada fallowland for a similar reason. In general, however, there is a close 1:1 relationship (r^2 = > 0.90) between these two data sets for crop districts that are not seriously affected by extraneous factors such as grasshoppers, and, where yield estimates were based on adequate sample sizes. Where there is limited acreage (e.g. CD #8A and 9B), there is frequently wide variation in field yields and poor opportunity of obtaining an accurate crop district estimate. Excessive spring moisture levels also contribute to wide variability in yield between the two data sources (e.g. CD #8A and 9B).

2. Comparison of Weather Based and Statistics Canada Estimates

The graphical presentation of Figure 2 shows a relationship (r = > 0.89 to 0.98) between the Weather-based and Statistics Canada yield estimates for crop districts in 1984 and 1985. In 1984 forecasts for grasshopper outbreaks were only moderate to severe for much of Saskatchewan (Mukerji and Baum) and few yields were classed as "outliers" from grasshopper damage. In 1985, weather-yield relationships were affected by high grasshopper populations. Forecasts in 1985 were for severe to very severe outbreaks within areas of Crop Districts #2, 3 and 4); and these were classed as "outlier" by their high deviation. Excessive spring rains occurred in north-eastern Saskatchewan which seriously affected seeding, emergence and growth particularly on fallowland (e.g. Crop Districts #5, 8, 9). The direct impact of weather on yield was high ($r = \geq 0.88$) when yields for crop districts seriously affected by the extraneous non-direct effects (insect damage, excess water) were removed from the regression relationship.

3. Relation of Yield Estimates to Seasonal Deficits

Analyses of crop district yields obtained from Statistics Canada in relation to derived weather parameters frequently identify the close impact of the shortfall in soil water required to meet evapotranspiration demands on the crop. The shortfall creates a water stress within the crop resulting in yield depression (Mack and Ferguson, 1968).

An illustration of the change in yield (Statistics Canada) of wheat on fallowland with change in the Seasonal Deficit is presented (Fig. 3) for 1984 and 1985 (r=-0.938 and -0.907, respectively). Crop districts which were seriously affected by severe insect damage or excess spring water were excluded. Similarly, there is a close relationship between the Crop Insurance yield data and the Seasonal Deficit for wheat grown on fallow and stubbleland (Fig. 4) for districts not seriously affected by excess spring rainfall and grasshoppers. Above normal precipitation in the spring of 1984 resulted in excess spring soil moisture which seriously delayed spring seeding. Yield estimates for Crop District 8 and 9 were depressed (Seasonal Deficit were near 0) in 1984 (Fig. 4). Grasshopper damage was forecasted in 1984 to be moderate to severe in parts of Crop Districts 2 and 3 and 7B and very severe in 1985 in Crop Districts 2, 3 and 4. The reduction in yield that occurred in Crop Districts #2 and 3 due to grasshoppers in 1985 on fallow is indicated in Fig. 4. This reduction may be determined for crop district 3AN by comparing the yield of 578 kg/ha to the regression line yield of 1494 kg/ha for the soil moisture conditions corresponding to a Seasonal Deficit of 220. Crop Districts 4A and 3BS would have had low yields (< 400 kg/ha) even without presence of grasshoppers as the Seasonal Deficits were extremely high (approximately 350 mm) for these two districts. Weather-based estimates were not significantly related to Seasonal Deficits in years when yields for all districts were grouped similarly at high levels (1850 to 2125 kg/ha) across the three climatic zones (Fig. 5).

The depressing effect of surplus water (very low deficit of < 25 mm) on yield is shown for the two years 1983 and 1984 in Figure 6. The calculated Seasonal Deficits in 1983 for the twenty districts ranged from a surplus of soil water of 98.3 mm to a shortfall of 158 mm (Fig. 6). The deficits for 1984 ranged between 4 and 282 mm. In both years yields were reduced under very low deficit conditions (< 25 mm). The yield data for 1983 were grouped into 2 categories with deficits ≤ 25 mm; deficits > 25 mm. The crop districts in 1984 which would be severely affected by grasshoppers were deleted from the crop weather relationship. A statistical analysis of this type of crop response was carried out using a two group (nested) regression analyses for each year with a linear and quadratic function i.e. a class interval was set whereby deficits of ≤ 25

mm were given a value of 0 and those > 25 mm were given +1. The analyses in Table 3 showed that yields were highly correlated with the deficit values (0.001 probability level) for both years. In 1983, surplus water (i.e. when Seasonal Deficit was < 25 mm) significantly reduced yields ($P = 0.01$), and the variation in the deficit > 25 had little significant effect on yield ($P = 0.10$). In 1984 when there was a wider range in deficits, yields were highly correlated with Seasonal Deficit.

A simultaneous equation based on the equation for each group in 1983 and in 1984 was used to calculate the minimum deficit possible for maximum yield. This calculation showed that yields were reduced when deficits less than 33.2 and 33.3 mm of water occurred in 1983 and 1984 respectively.

4. To calculate a "Statistics Canada" provincial production estimate from "Weather-Based" production estimates

The relationship between weather-based production estimates and Statistics Canada for years 1979 to 1988 is shown in Figure 7. For eight of the ten years the relationship followed the following equation with a correlation coefficient of $R = 0.981$ and a C.V. = 3.58.

$$\hat{P}_{ST} = 0.246 + 0.796\ P_{WB} + 0.00429\ P_{WB}^2$$

where $\hat{P}_{ST}$: Predicted production calculated from production estimates based on weather-based yields regressed against Statistics Canada historical records.

P_{WB}: Production estimates for the province from the crop production estimates of the 20 crops districts.

DISCUSSION AND CONCLUSIONS

The evaluation of the three data sources on a crop district basis shows that there is comparable relationship between the Crop Survey estimates and the Crop Insurance Records in Saskatchewan for yields of wheat grown on fallowland (1981-85). The lack of breakdown of fertilized and unfertilized yields in the Statistics Canada data set prevents a precise comparison between the two sets. However, the difference between the two is reasonably explainable from known agronomic and crop management principals. Thus, the Crop Insurance data may be used where detailed breakdown of yield information is needed and is not available from Statistics Canada.

The relationship of crop yields estimated from weather based parameters is also associated in general with yields determined from either of the other two data sources when weather is the dominant factor directly causing variation in yield. When external factors (insects, flooding) seriously modify the effects of the weather factors, the weather derived estimates provide an indication of the extent of damage. The Seasonal Water Deficit approach for analyzing weather data in relation to crop growth is shown to be a good parameter for estimating crop district yields.

Production estimates based on weather-based yield model determined on July 31 were closely related to the production estimates published in December by Statistics Canada for seven out of eight years. The assessment shows that edited Crop Insurance data is a valid data source for future development of procedures for estimating crop yields which are relevant to the dominant crop management practices used in dryland agricultural lands of the prairies.

Since, Crop Insurance Records compare favorably with Statistics Canada overall yield estimate for a crop district, it is proposed that edited crop insurance records be considered as a basis for future development of operational procedures for estimating crop yields and production. The Crop Insurance Records provide information on the major farm management practices that are carried on within the Soil Climatic Zones and crop districts of Saskatchewan. As there is a wide variation in yield and acreage associated with these major management practices, it is important that each be considered separately in the production estimation when conducting weather impact analyses in the prairies.

In conclusion, this study showed that eight of the ten years between 1979 to 1988, weather based production estimates of wheat made in July for the province of Saskatchewan were correlated (R=0.98) to Statistics Canada estimates published the following year. This has been achieved by introduction of procedures for estimating yields separately for fallow and stubble management practices and having timely weather data available for an average of 1.5 observation stations per crop district. During this period, extreme weather and production levels occurred. Two of the ten years had marginally higher estimates from Weather-Based model than from Statistics Canada due partly to higher production from the non spring wheat grain than accountable for the remaining years.

ACKNOWLEDGEMENTS

Appreciation is extended to the Saskatchewan Crop Insurance Corporation for providing the yield data for crop management factors and to Statistics Canada in supplementing unpublished estimates and comments relative to this publication.

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List of Figures

Fig. 1. Relationship between Crop District yields from Crop Insurance field records and yields from Statistics Canada, Crop Survey data for fallow and stubbleland for 1984 and 1985. The symbol o identifies Crop District yield data deviating significantly from the regression and which were not included in the general relationship. Districts were excluded from the linear regression where there was excess spring water and severe insect damage. Some of these outlier yields also were calculated from limited acreages (e.g. < 404 ha). The statistics a, b, and r represent the intercept, slope, and correlation coefficient.

Fig. 2. Relationship between crop district yields estimates from Weather-based procedures yields estimates by Statistics Canada. Outlier yields affected by extraneous factors (grasshopper o and flooding *) are excluded. Y_{xx} represents the mean value for a provincial estimate based on xx crop district yields. The statistics a, b, and r represent the intercept, slope, and correlation coefficient.

Fig. 3. Relationship between Crop district yields estimate by Statistics Canada and Seasonal Water deficits based on accumulated precipitation over a 21-month period prior to seeding. The symbol θ identifies yields for crop districts significantly different from the regression. These crop districts had large grasshopper populations. Outlier yields affected by extraneous factors of grasshopper and flooding are excluded.

Fig. 4. Relationship between crop district wheat yields from Crop Insurance Field records and Seasonal Water Deficits for fallowland crops (precipitation data accumulated for a 21-month period) and for stubble crop (precipitation accumulated for 8-month period) prior to seeding May 1. The symbol θ identifies yields of crop districts deviating from the main relationship i.e. Districts 8 and 9 in the Black Zone received abnormally high spring precipitation and District 2 and 3 which had very high grasshopper populations.

Fig. 5. Relationship between crop districts wheat yields from Crop Insurance Field records and Seasonal Water Deficits calculated for fallowland in 1980 and 1981 when Seasonal Water Deficits were generally low.

Fig. 6. Comparison of yields (Statistics Canada) to Seasonal Water Deficit below and above the 25 mm for 1983 and 1984.

Fig. 7. The relationship between weather-based production estimates for Saskatchewan and Statistics Canada production estimates for the province.

TABLE 1. THE VARIATION IN WHEAT YIELDS AND AREA (1982 TO 1985) UNDER FOUR CROP MANAGEMENT PRACTICES IN THREE CROP DISTRICTS FOR THREE SOIL CLIMATIC ZONES IN SASKATCHEWAN

Soil Climatic Zone Crop District Cropping Practice	1982		1983		1984		1985	
	Not Fert.	Fert.	Not Fert.	Fert.	Not Fert.	Fert.	Not Fert.	Fert.
A: Yield	Kg per hectare							
Brown								
4A Fallow	1842	2193	2057	2031	780	1090	282	567
Stubble	1029	1573	1055	1452	107	242	208	410
mean yield $\bar{y}$; S.D.	1654±490		1647±482		558±455		370±135	
Wt mean yield*	1903		1876		726		365	
Dark Brown								
1A Fallow	1770	2192	1513	1526	1265	1775	1224	2213
Stubble	1110	1688	982	1459	(679)	1298	975	1863
mean yield $\bar{y}$; S.D.	1688±444		1365±262		1257±451		1567±572	
Wt mean yield*	1822		1550		1385		1372	
Black								
9B Fallow	1970	2576	1957	2623	1540	2092	1486	2334
Stubble	1257	2212	1042	2098	(1795)	2058	720	2125
mean yield $\bar{y}$; S.D.	2004±558		1930±660		1869±256		1668±726	
Wt mean yield*	2286		2200		2065		2125	
B: Area	thousand hectares							
Brown								
4A Fallow	39.0	12.4	44.8	20.0	56.5	30.2	44.5	20.0
Stubble	0.92	1.36	5.94	14.3	4.80	16.2	5.94	14.3
Dark Brown								
1A Fallow	46.3	28.5	40.6	12.5	28.5	9.69	35.6	6.47
Stubble	6.43	25.4	0.92	2.15	0.26	1.62	0.75	0.70
Black								
9B Fallow	2.51	13.4	1.58	10.9	1.49	7.44	0.96	7.13
Stubble	0.70	31.2	0.70	32.8	0.39	37.6	0.57	49.7

Data from Saskatchewan Crop Insurance Records.

* Mean yields weighted for relative acreage of each of the four management practices.

( ) Limited sample size- ha

$$S.D.\bar{y} = \sqrt{\frac{\Sigma(y-\bar{y})^2}{n-1}}$$

TABLE 2. COMPARISON OF PROVINCIAL MEAN YIELDS OF WHEAT AND STANDARD DEVIATION OF THE CORRESPONDING 20 CROP DISTRICT YIELD VALUES (FALLOW)

Crop Year	Unweighted mean yields - kg/ha A Crop Insurance Records mean	SD (95%)	B Statistics Canada mean	SD (95%)	C Weather-based Estimates Fallow mean	SD (95%)	Correlation (r) and regression (b) coefficients A vs B r	b	B vs C r	b
Weather-based estimates using 18 stations for Saskatchewan										
1979	N.A.	N.A.	1649*	516	1742	536	N.A.		.53	.80
1980	1850	385	1753*	545	1917	218	.89	.67	.50	.25
1981	2125	521	2034	488	2072	443	.93	.88	.67	.36
1982	2401	355	2287	430	1971	298	.88	.73	.21	.15
Weather-based estimates using 30 stations for Saskatchewan										
1983	2105	471	2058	487	2044	312	.95	.91	$.99^{n}$	.68
1984	1708	591	1655	702	1694	633	.94	.80	.93	.69
1985	1789	1240	1729	1313	1742	1311	.97	.93	.98	.90
1986	N.A.		(2159)	N.A.	2146	249	-	-	-	-

* Unpublished data
N.A. Not available

$$S.D._{(.95)} = \sqrt{\frac{\Sigma(y-\bar{y})^2}{n-1}} \; {}^{*}t_{.95(n)}$$

$^{*}t_{.95}$ Where n is the number of pairs crop districts comprising the means.

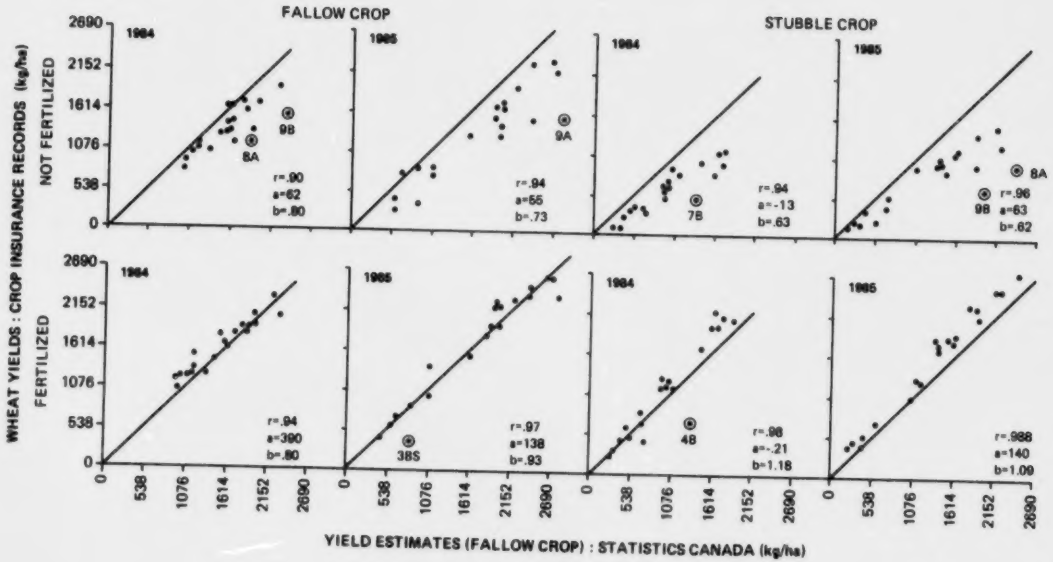

FALLOW CROP
STUBBLE CROP
WHEAT YIELDS : CROP INSURANCE RECORDS (kg/ha)
NOT FERTILIZED
FERTILIZED
YIELD ESTIMATES (FALLOW CROP) : STATISTICS CANADA (kg/ha)
0
538
1076
1614
2152
2690
1984
1985
8A
9B
r=.90
a=62
b=.80
9A
r=.94
a=55
b=.73
7B
r=.94
a=-13
b=.63
8A
9B
r=.96
a=63
b=.62
r=.94
a=390
b=.80
38S
r=.97
a=138
b=.93
4B
r=.98
a=-.21
b=1.18
r=.988
a=140
b=1.09

FIGURE 1

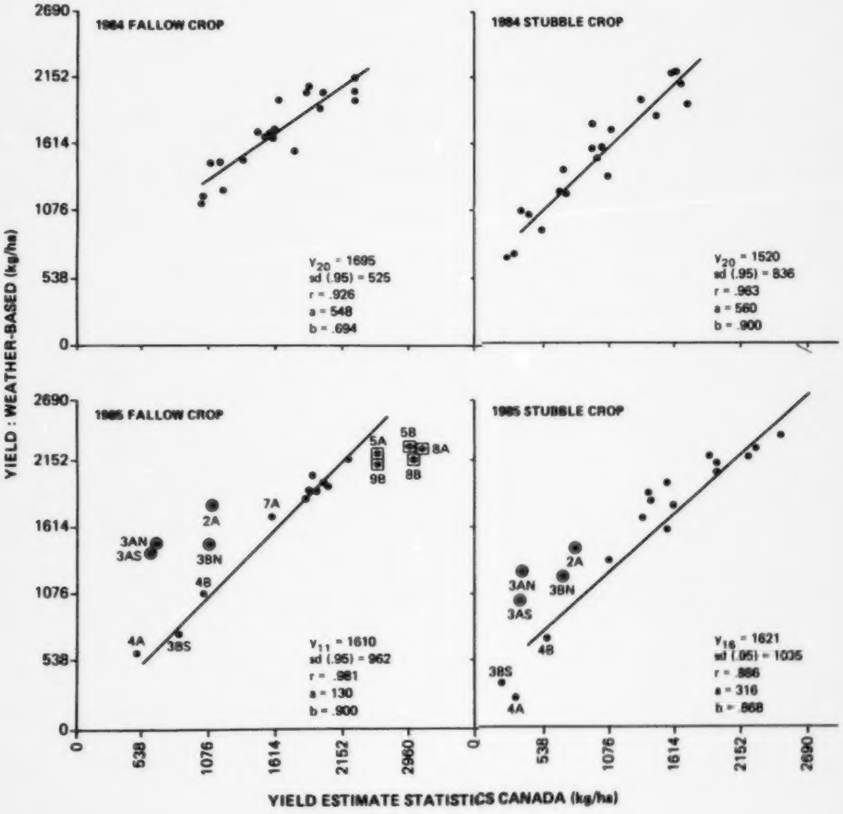

1984 FALLOW CROP
1984 STUBBLE CROP
1985 FALLOW CROP
1985 STUBBLE CROP
YIELD : WEATHER-BASED (kg/ha)
2690
2152
1614
1076
538
0
YIELD ESTIMATE STATISTICS CANADA (kg/ha)
0
538
1076
1614
2152
2960
2690
Y20 = 1695
sd (.95) = 525
r = .926
a = 548
b = .694
Y20 = 1520
sd (.95) = 836
r = .963
a = 560
b = .900
Y11 = 1610
sd (.95) = 962
r = .981
a = 130
b = .900
Y16 = 1621
sd (.95) = 1035
r = .886
a = 316
b = .868
3AN
3AS
2A
3BN
4B
4A
3BS
7A
5A
9B
5B
8A
8B

FIGURE 2

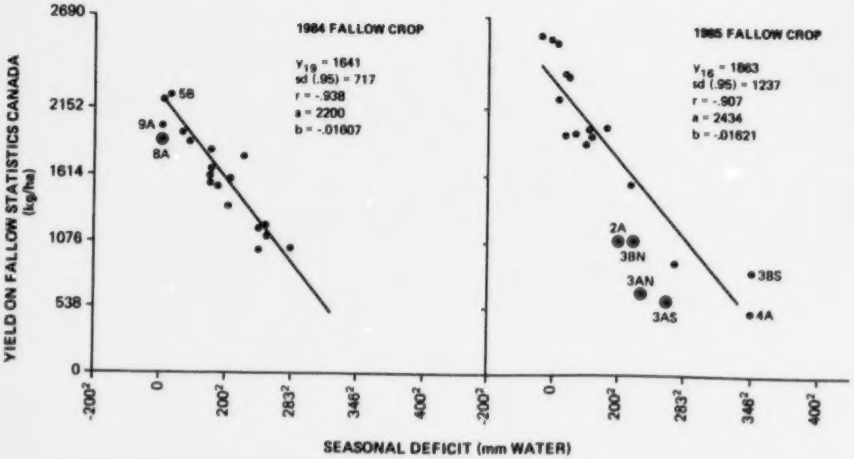

YIELD ON FALLOW STATISTICS CANADA (kg/ha)
2690
2152
1614
1076
538
0
1984 FALLOW CROP
$\bar{Y}_{19}$ = 1641
sd (.95) = 717
r = -.938
a = 2200
b = -.01607
5B
9A
8A
1985 FALLOW CROP
$\bar{Y}_{16}$ = 1863
sd (.95) = 1237
r = -.907
a = 2434
b = -.01621
2A
3BN
3AN
3AS
3BS
4A
-200^2
0
200^2
283^2
346^2
400^2
-200^2
0
200^2
283^2
346^2
400^2
SEASONAL DEFICIT (mm WATER)

FIGURE 3

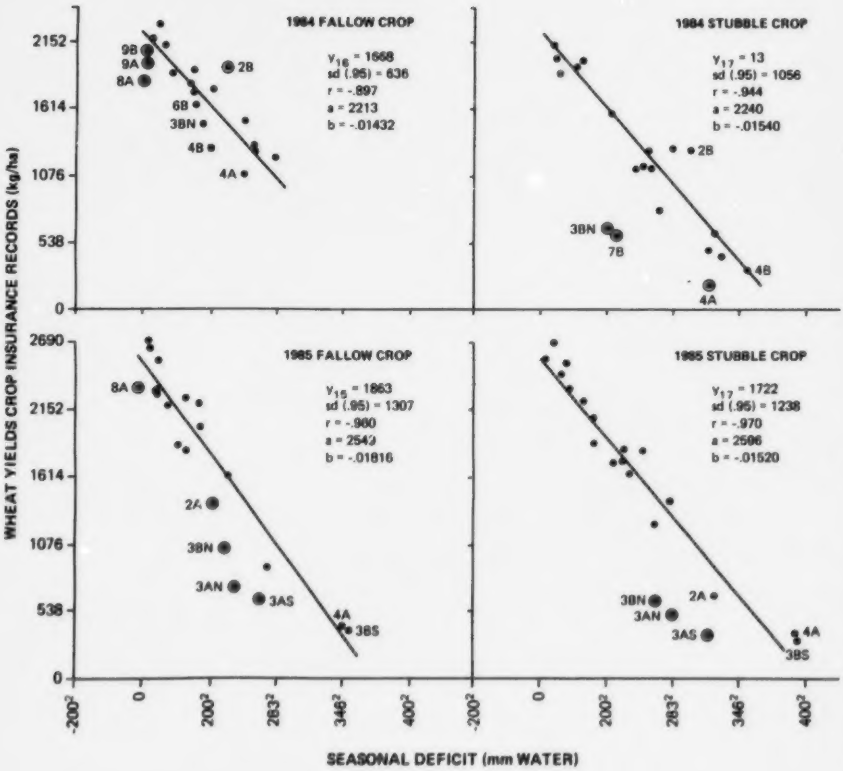

1984 FALLOW CROP
Y_{16} = 1668
sd (.95) = 636
r = -.897
a = 2213
b = -.01432
9B
9A
8A
2B
6B
3BN
4B
4A
1984 STUBBLE CROP
Y_{17} = 13
sd (.95) = 1056
r = -.944
a = 2240
b = -.01540
2B
3BN
7B
4B
4A
1985 FALLOW CROP
Y_{15} = 1863
sd (.95) = 1307
r = -.960
a = 2543
b = -.01816
8A
2A
3BN
3AN
3AS
4A
3BS
1985 STUBBLE CROP
Y_{17} = 1722
sd (.95) = 1238
r = -.970
a = 2506
b = -.01520
3BN
2A
3AN
3AS
4A
3BS
WHEAT YIELDS CROP INSURANCE RECORDS (kg/ha)
2152
1614
1076
538
0
2690
2152
1614
1076
538
0
-200^2
0
200^2
283^2
346^2
400^2
-200^2
0
200^2
283^2
346^2
400^2
SEASONAL DEFICIT (mm WATER)

FIGURE 4

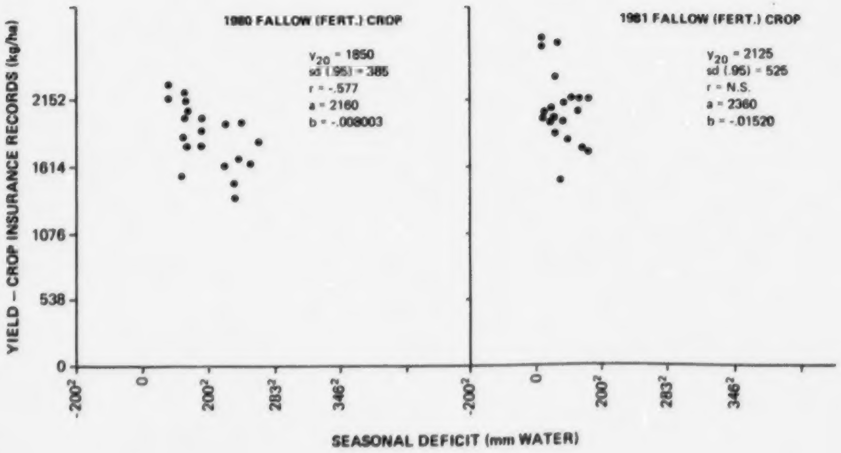

YIELD – CROP INSURANCE RECORDS (kg/ha)
2152
1614
1076
538
0
1980 FALLOW (FERT.) CROP
Y_{20} = 1850
sd (.95) = 385
r = -.577
a = 2160
b = -.008003
1981 FALLOW (FERT.) CROP
Y_{20} = 2125
sd (.95) = 525
r = N.S.
a = 2360
b = -.01520
-200^2
0
200^2
283^2
346^2
-200^2
0
200^2
283^2
346^2
SEASONAL DEFICIT (mm WATER)

FIGURE 5

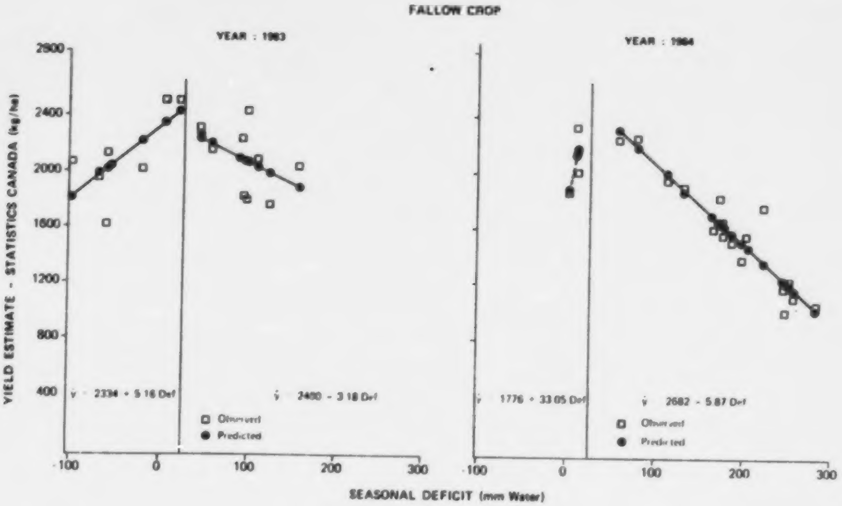

FALLOW CROP
YEAR : 1983
YEAR : 1984
YIELD ESTIMATE - STATISTICS CANADA (kg/ha)
2800
2400
2000
1600
1200
800
400
ŷ = 2334 + 5.16 Def
ŷ = 2400 - 3.18 Def
ŷ = 1776 + 33.05 Def
ŷ = 2682 - 5.87 Def
□ Observed
● Predicted
-100
0
100
200
300
SEASONAL DEFICIT (mm Water)

Figure 6

TABLE 3. STATISTICAL ANALYSES (NESTED REGRESSION) OF YIELD DATA FOR TWO YEARS WHEN THE SOIL MOISTURE DEFICIT WAS UNDER 25 MM FOR SEVERAL CROP DISTRICTS

	1983					1984				
Source	DF	M.S.	F	b	R^2	DF	M.S.	F	b	R^2
Model	4	4234.3	342**		.99	4	3216.5	683**		.99
$\leq$ 25 mm	2		238**	3.18*		2		312**	33.0	
> 25 mm	2		3	-5.16		2		53**	-5.87**	
Error	13	12.3				16	4.7			

* Significant at 0.05 Level of probability or better

** Significant at 0.01 Level of probability or better

n Based on a 2-class nested regression variable: Group 0 = $\leq$ 25 mm deficit and Group 2 = > 25 mm deficit with analysis of covariance conducted on this variable. A standard linear or quadratic equation would not represent the scatter of the data points

b Regression Coefficient (Linear).

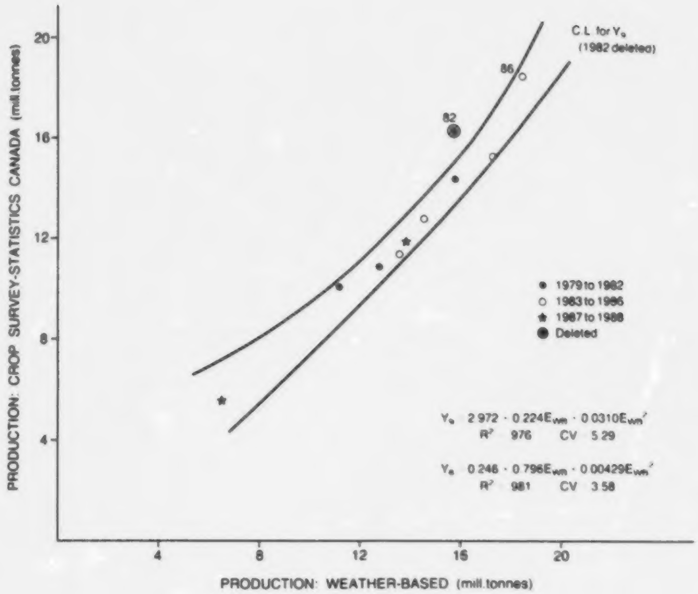

PRODUCTION: CROP SURVEY-STATISTICS CANADA (mill.tonnes)
PRODUCTION: WEATHER-BASED (mill.tonnes)
4
8
12
16
20
4
8
12
16
20
C.L. for Y_e
(1982 deleted)
86
82
● 1979 to 1982
○ 1983 to 1986
★ 1987 to 1988
● Deleted
Y_e 2 972 · 0 224E_{wm} · 0 0310E_{wm}^2
R^2 976 CV 5 29
Y_e 0 246 · 0 796E_{wm} · 0 00429E_{wm}^2
R^2 981 CV 3 58

FIGURE 7

TABLE 4. CROP PRODUCTION PREDICTED FROM REGRESSION OF WEATHER-BASED ESTIMATES TO STATISTICS CANADA HISTORICAL RECORD FOR EIGHT OF TEN YEARS.

Year	Weather Based Estimates (July)	Statistics Canada Estimates (Dec.)	Calculated Production from Regression of Weather-based Estimates to Statistics Canada Records. $Y=0.246+0.796\,E_{WB}+0.00429\,E_{WB}^2$ S.E.=.242 .31 .0131				
					Confidence Limits		
			Predicted Crop Production	Standard Error	Lower 95%	Upper 95%	Type of Wheat /Regression
	mt	mt	mt	mt	mt	mt	
1979	10.98	10.18	9.5043	0.2322	8.9075	10.1011	All Wheat
1980	12.80	10.83	11.1390	0.2021	10.6195	11.6584	All Wheat
1981	15.92	14.28	14.0074	0.2105	13.4664	14.5485	All Wheat
1983	17.19	15.21	15.1990	0.3396	14.3260	16.0719	All Wheat
1984	13.65	11.48	11.9122	0.1809	11.4472	12.3771	All Wheat
1985	14.64	12.87	12.8205	0.1665	12.3926	13.2484	All Wheat
1986	18.35	18.37	-	-	-	-	All Wheat
1987	13.81	11.91	12.0584	0.1772	11.6029	12.5139	Spring Wheat
1988	6.45	5.44*	5.5592	0.4061	4.5153	6.6031	Spring Wheat

* Initial estimate by Statistics Canada, August 1988
R^2 = .981 C.V. 3.58. Based on production data for eight out of ten years.
E_{WB}: Weather-based Estimate.

Table 5. RANGE IN PREDICTED PRODUCTION BASED ON EQUATION FOR NINE OUT OF TEN YEARS

Year	Weather Based Estimates (July)	Statistics Canada Estimates (Dec.)	Calculated Value for Statistics Canada Estimates from Weather-based Regression: $Y=2.972+0.224\ E_{WB}+0.03107\ E_{WB}{}^2$ $R^2=.976$;CV= 5.29 S.E.=2.41 .39 .015				
			Predicted Yield	Stand. Error	Confidence Limits 95%	95%	Type of Wheat /Regression
	mt	mt	mt	mt	mt	mt	
1979	10.98	10.18	9.1838	0.3288	8.3792	9.9884	All Wheat
1980	12.80	10.83	10.9372	0.3020	10.1982	11.6763	All Wheat
1981	15.92	14.28	14.4220	0.2587	13.7888	15.0551	All Wheat
1983	17.19	15.21	16.0136	0.3464	15.1660	16.8613	All Wheat
1984	13.65	11.48	11.8266	0.2819	11.1370	12.5163	All Wheat
1985	14.64	12.87	12.9191	0.2577	12.2886	13.5497	All Wheat
1986	18.35	18.37	17.5551	0.5066	16.3155	18.7947	All Wheat
1987	13.81	11.91	11.9991	0.2777	11.3196	12.6786	Spring Wheat
1988	6.45	5.44*	5.7134	0.6354	4.1587	7.2681	Spring Wheat

* Initial production estimate by Statistics Canada, August 1988
R^2 = .976 C.V. 5.295
E_{WB}: Weather-based Estimate

Crop Moisture Index (CMI)
Palmer Drought Index (PDI)

K. Jones

The Crop Moisture Index is used extensively in the U.S. to provide broad-scale soil moisture conditions over the major growing areas.

- Rapid response to changes in soil moisture.
- Stands at zero at start of growing season.
- Highly dependent on precipitation and potential evapotransporation over the last week.

The Palmer Drought Index is used extensivlely in the U.S. to provide broad-scale hydrological moisture conditions over the entire U.S.

- Very conservative and slow to change.
- Runs over entire year.
- Highly dependent on previous months value.

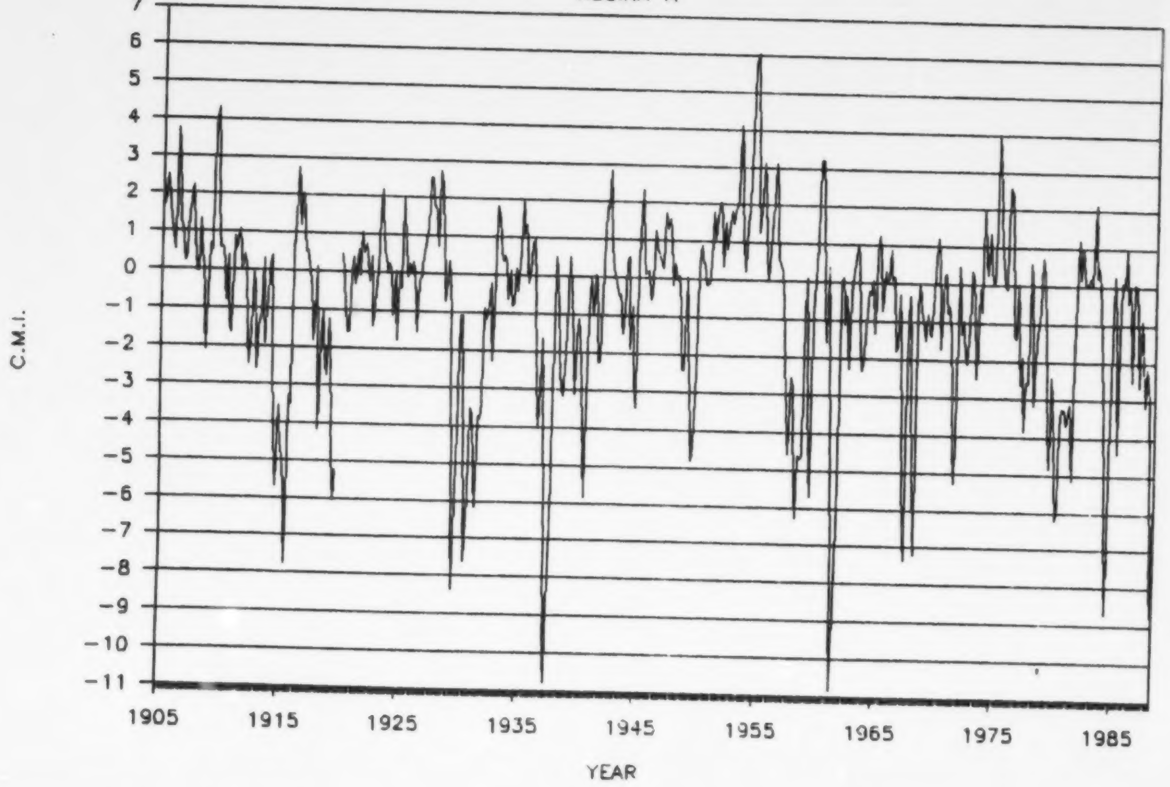
CROP MOISTURE INDEX
SHORT TERM CHANGE
OF AGRICULTURAL DROUGHTS

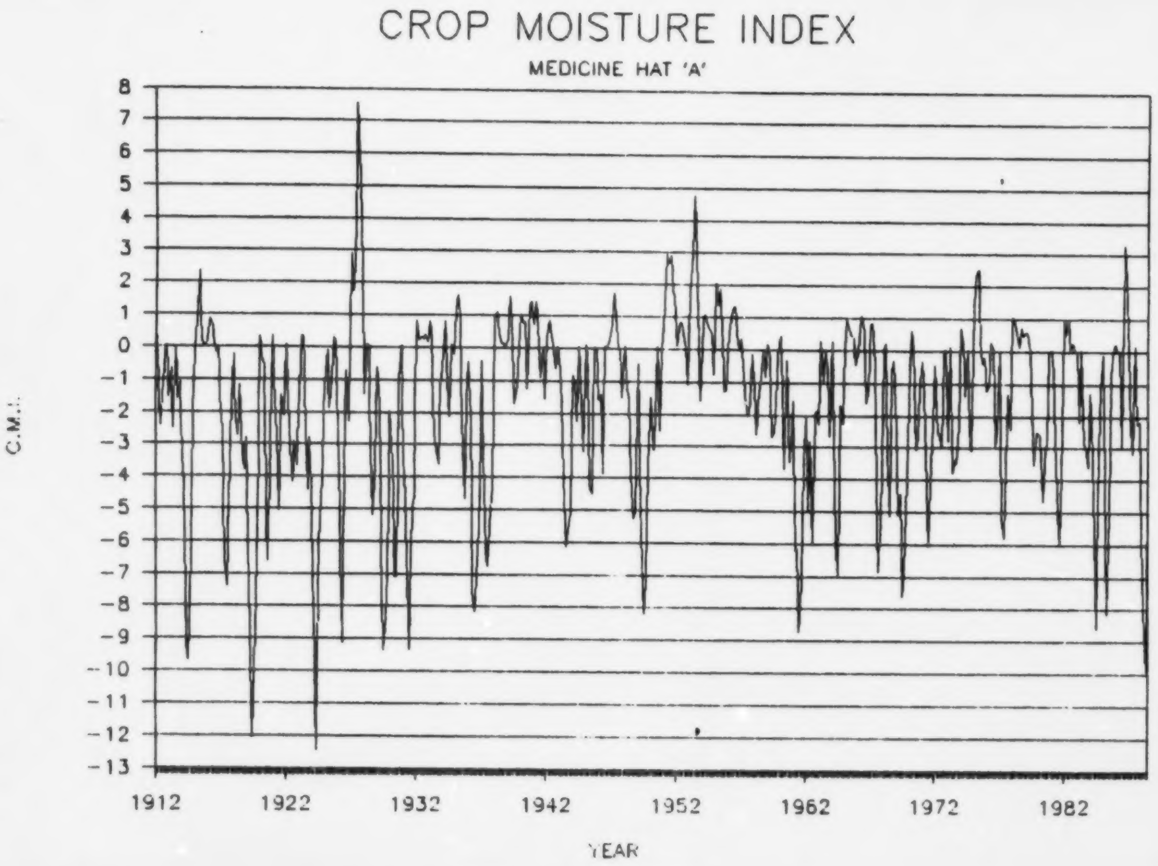
MEASURES BROAD SCALE SHORT TERM
CONDITIONS OVER MAJOR GROWING AREAS

STANDS AT ZERO AT THE START OF GROWING SEASON
AND RETURNS TO ZERO AT THE END OF GROWING SEASON

CROP MOISTURE INDEX

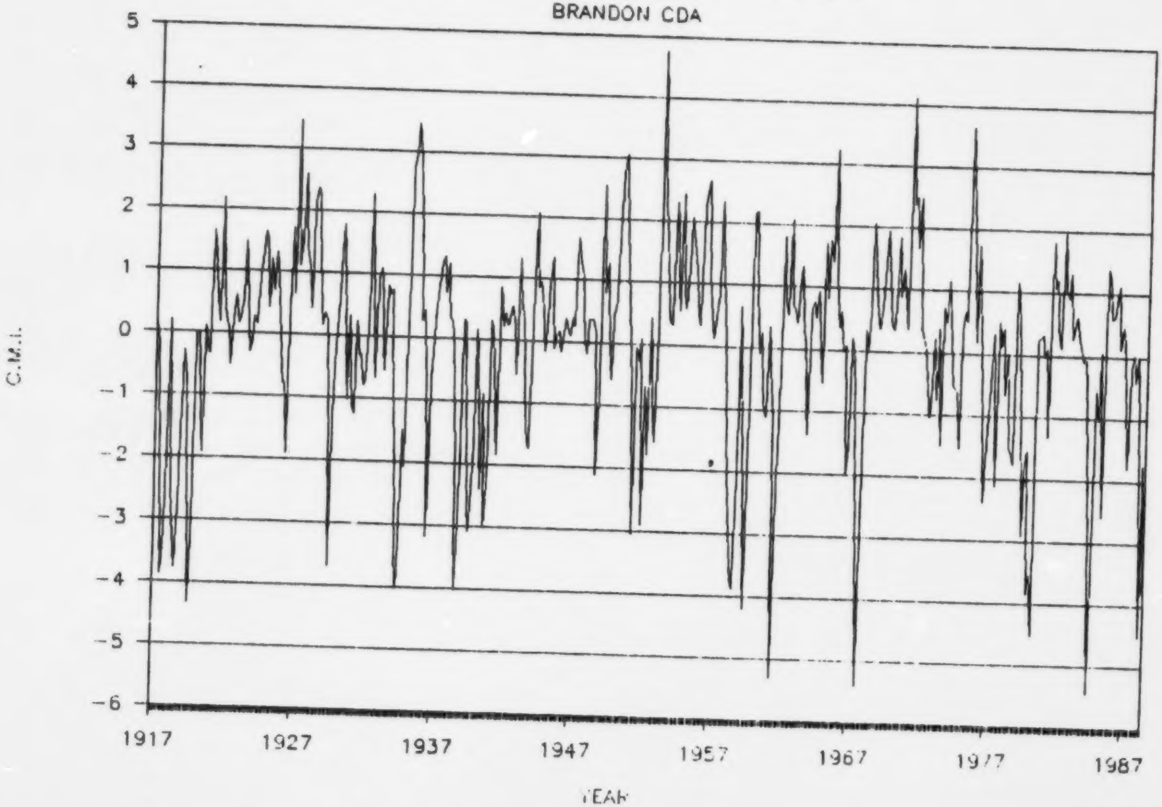
REGINA 'A'




CROP MOISTURE INDEX
MEDICINE HAT 'A'
C.M.I.
8
7
6
5
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
−8
−9
−10
−11
−12
−13
1912
1922
1932
1942
1952
1962
1972
1982
YEAR

CROP MOISTURE INDEX

BRANDON CDA



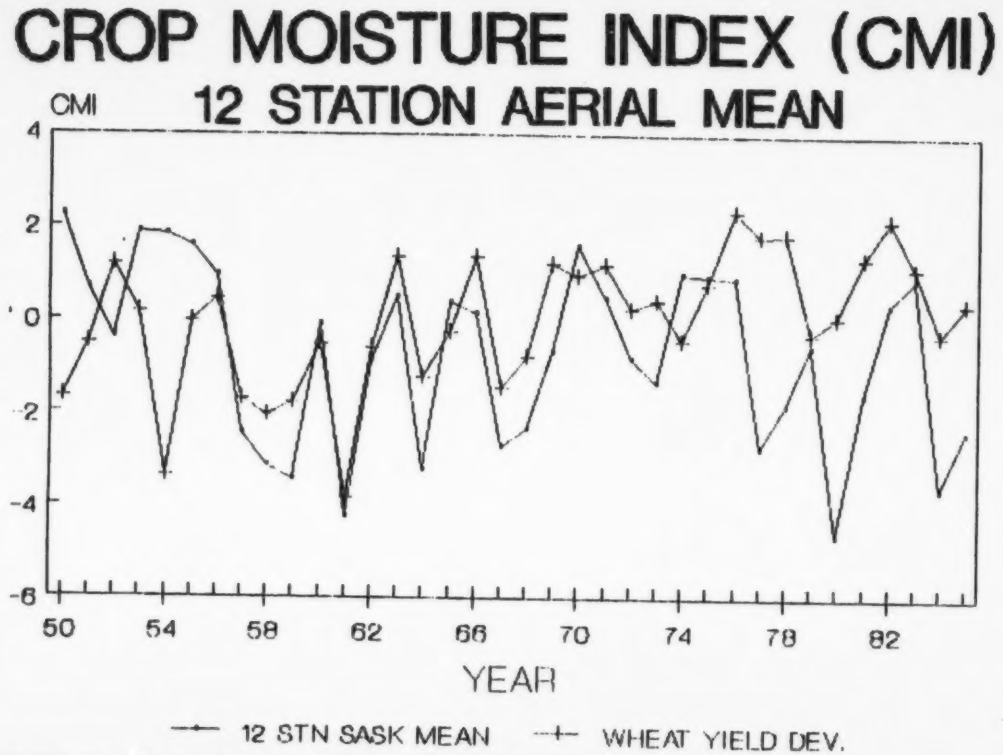


FIGURE 11: 12 STATION SASK. MEAN OF CROP MOISTURE INDEX
AND
WHEAT YIELD DEVIATION FROM NORMAL (kg/acre) in
100's FOR PROVINCE OF SASKATCHEWAN 1950 - 1985

CROP MOISTURE INDEX (CMI)
REGINA 'A'

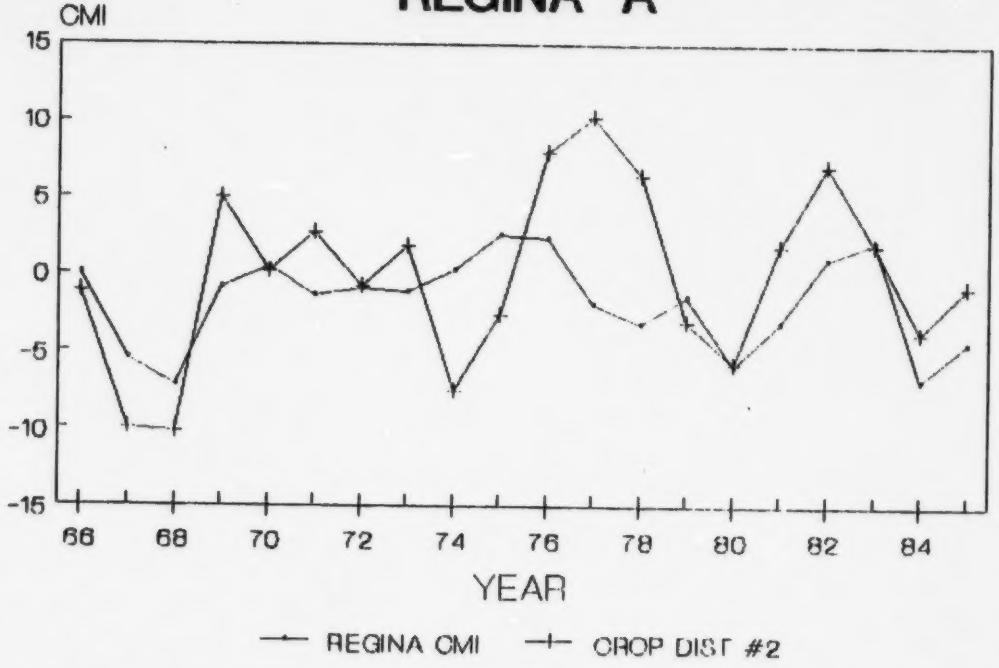


FIGURE 12: CROP MOISTURE INDEX FOR REGINA 'A' AND WHEAT YIELD DEVIATION FROM NORMAL (kg/acre) IN 25's FOR CROP DISTRICT #2 1966 - 1985

CROP MOISTURE INDEX (CMI)

KINDERSLEY

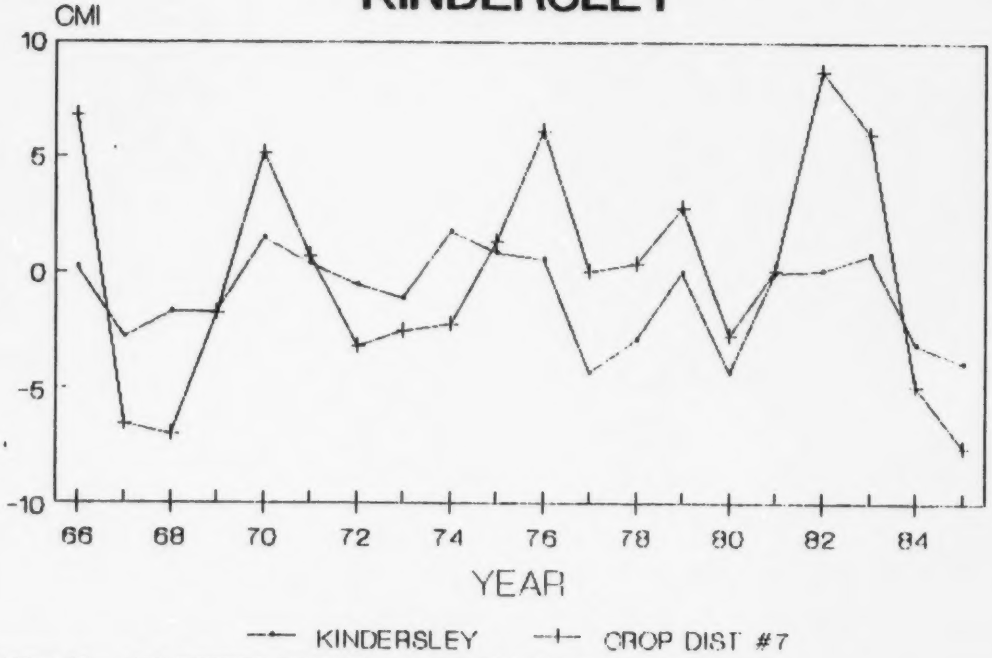


FIGURE 13: CROP MOISTURE INDEX FOR KINDERSLEY AND WHEAT YIELD DEVIATION FROM NORMAL (kg/acre) IN STEPS OF 25 FOR CROP DISTRICT #7 1966 - 1985

P.D.I.

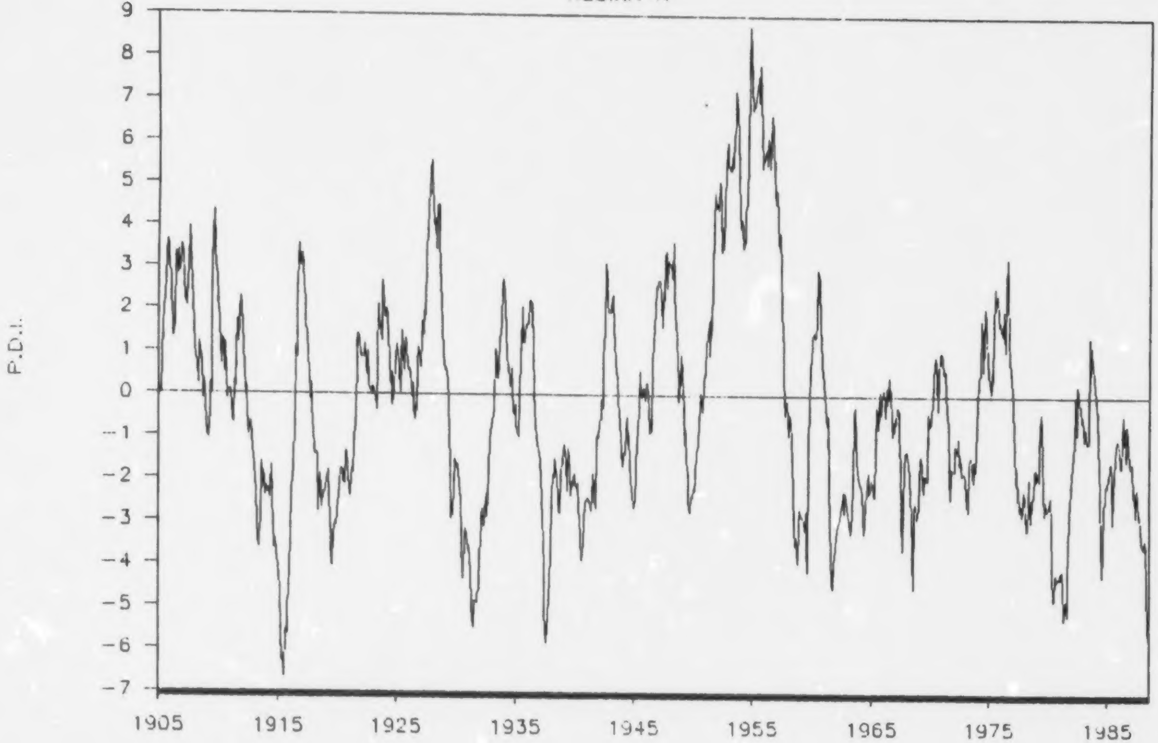
HISTORIC ANALYSIS OF DROUGHTS

MEASURES THE DEGREE TO WHICH THE WEATHER HAS BEEN ABNORMALLY DRY OR WET

UNIVERSAL IN THAT PERSISTENTLY NORMAL TEMPERATURE AND PRECIPITATION PRODUCE AN INDEX NEAR ZERO IN ALL SEASONS IN ALL CLIMATES.

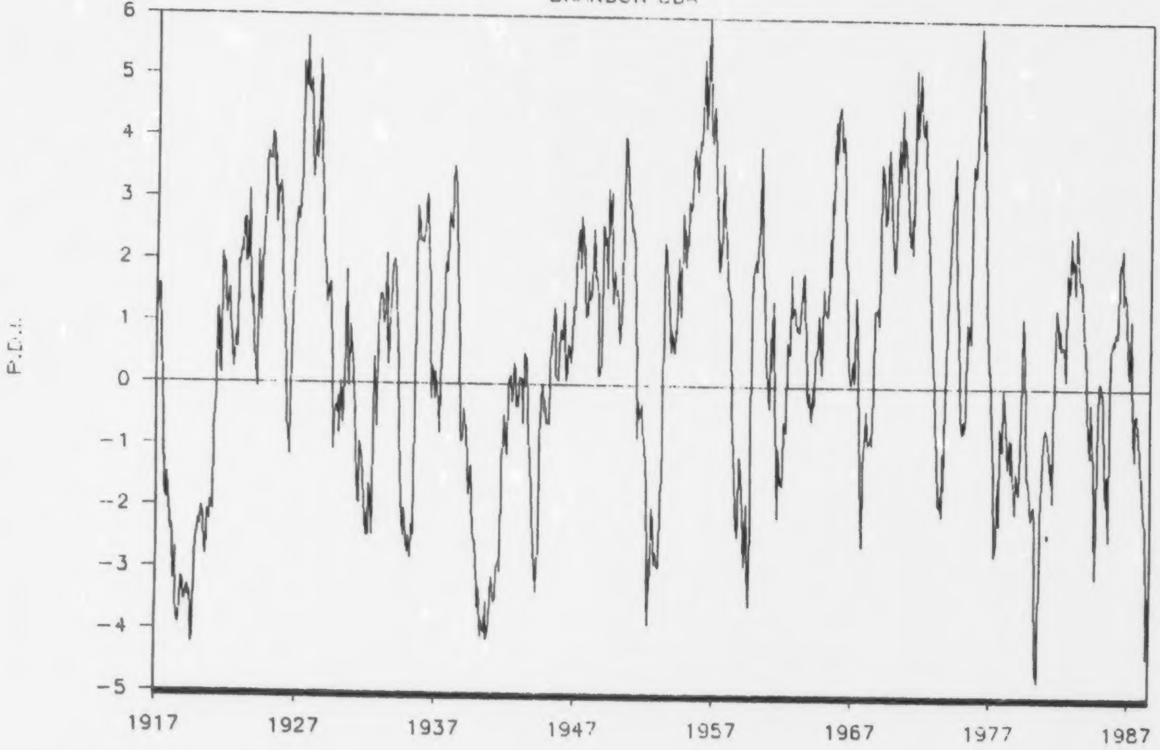
PALMER DROUGHT INDEX

REGINA 'A'



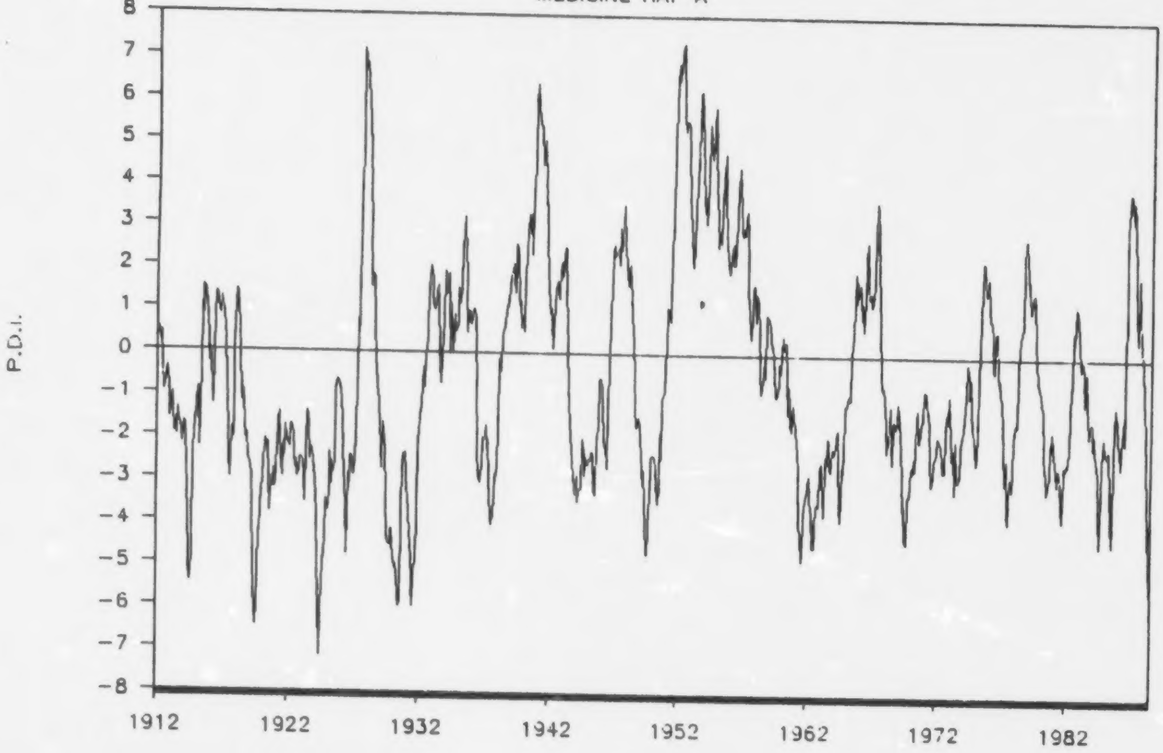
PALMER DROUGHT INDEX

BRANDON CDA



PALMER DROUGHT INDEX

MEDICINE HAT 'A'



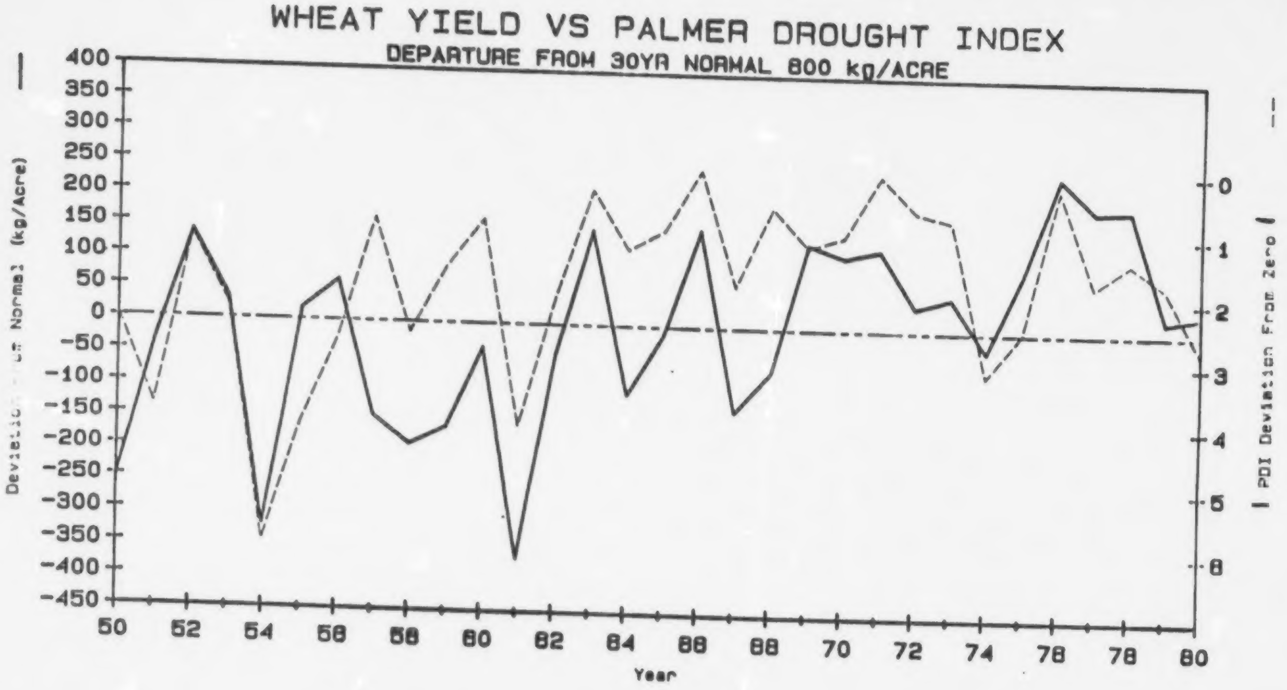


FIGURE 2: Wheat yield deviations from 30 year normal for Saskatchewan and absolute value of Palmer Index (month October) for 1950 to 1980.

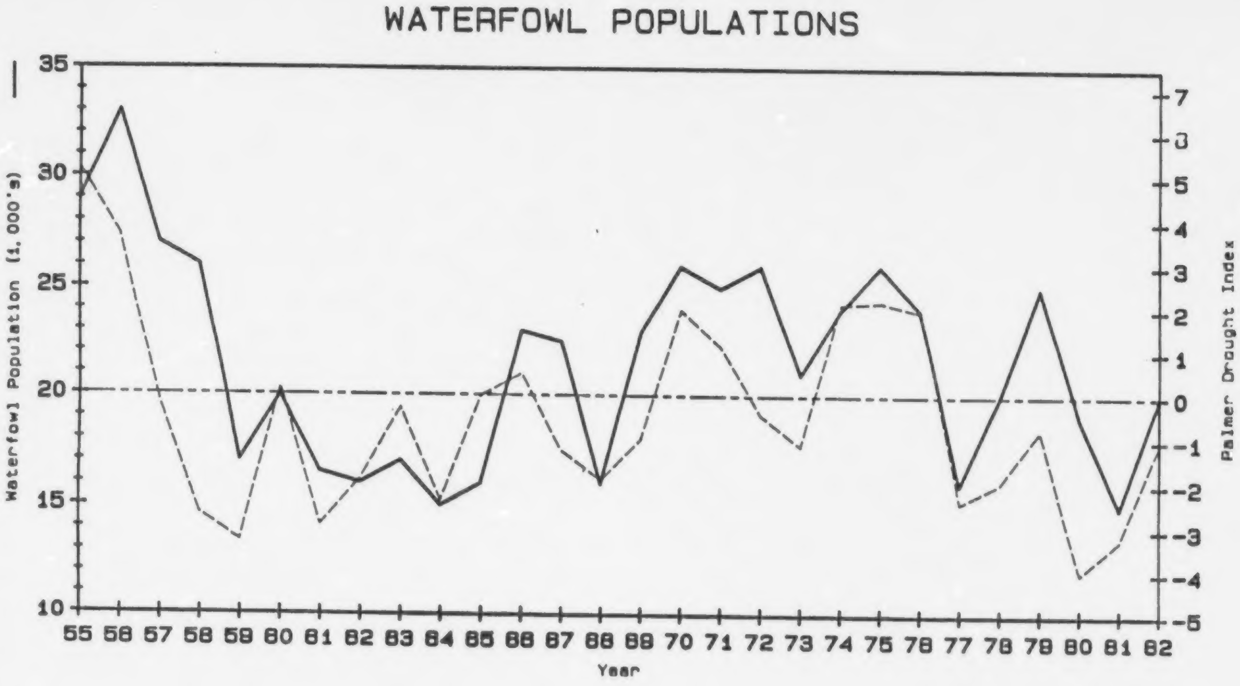


FIGURE 1: Waterfowl populations (1,000's) and mean P.D.I. values for 11 stations in Saskatchewan in July 1955 to 1982.

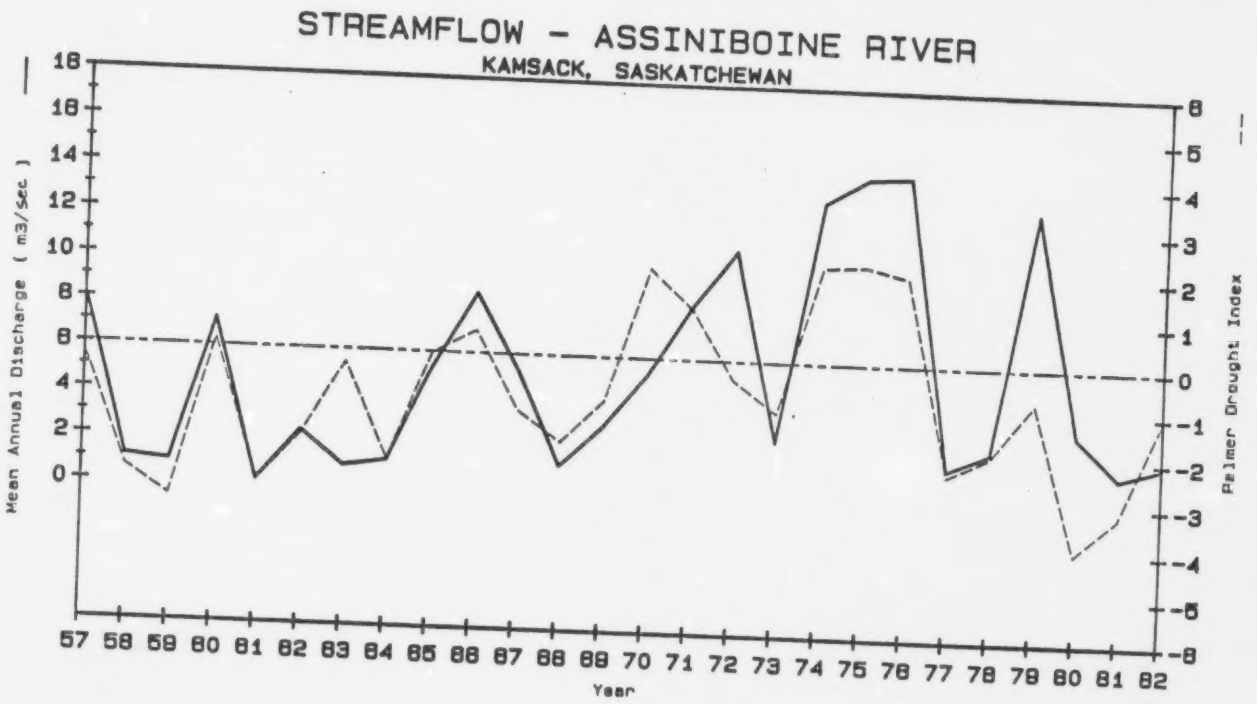


FIGURE 3: Mean annual discharge of the Assiniboine River at Kamsack and mean Palmer Index for 11 stations in Saskatchewan (month July) for 1957 to 1982.

FREQUECY ANALYSIS
OF
METEOROLOGICAL DROUGHT
IN THE
SASKATCHEWAN PORTION
OF THE
SOUTH SASKATCHEWAN RIVER BASIN

D. J. BAUER
and
L. E. Welsh

HYDROCLIMATOLOGY SECTION
HYDROMETEOROLOGICAL RESEARCH DIVISION
CANADIAN CLIMATE CENTRE

Purpose of the Study

This study was undertaken in order to investigate, using monthly precipitation data, the climatology of drought in the Saskatchewan portion of the South Saskatchewan River Basin (SSRB). Local precipitation in the basin does not contribute substantially to the annual flow in the South Saskatchewan River; however, it does have an impact on water use in the basin. Therefore, an analysis of the frequency and severity of drought could be of use in planning to meet future water requirements in the basin. Statistics on the frequency, duration and severity of significant droughts are required by the South Saskatchewan River Basin Study Board to plan the long-term operation of the basin.

Data

Thiessen polygon analysis of monthly precipitation data from 12 stations in the basin were used to calculate a monthly precipitation value for each of six sub-regions in the basin. (Figure 1). Initial analysis was done for the period 1912 (or 1922) to 1985. Recently data up to and including July 1988 were added to the analyses for sub-regions 2 and 4.

Effective Precipitation

Rather than identifying periods of meteorological drought on the basis of monthly precipitation directly, it was decided that the results could be more meaningful if the carry-over effect of precipitation deficits and surpluses were considered in some way. Therefore, "effective precipitation" (EP), a concept introduced by Herbst et al. (1966), was used in this analysis. The concept is based upon the assumption that the benefit of above average precipitation due to storage of moisture in the soil (rainfall) or in the snowpack (snowfall) persists for some time after the event and, conversely, recovery from below normal precipitation is likewise not necessarily immediate. Effective precipitation is defined as the actual precipitation (AP), for the month plus a carry-over (CO), from the previous month. The amount of carry-over (positive or negative) is dependent upon the difference between actual and average precipitation for the month and an appropriate weighting factor. Since the carry-over would be of greater significance during the growing season when precipitation is normally higher, the weighting factors were related to average monthly and average annual precipitation. Weighting factors for each of the twelve months were calculated as follows:

$$W_i = 0.1 \left(1 + \frac{AMP}{AAP/12}\right)$$

where: W_i = weighting factor for the i^{th} month
AMP = average monthly precipitation for that month and

AAP = average annual precipitation for the period of record.

Weighting factors were thus calculated for each of the twelve months for each of the six sub-regions. Weighting factors ranged from 0.15 in the winter months to a high of 0.34.

The carry-over was then calculated by multiplying the surplus or deficit (actual precipitation for the month minus the average precipitation for that month) by the weighting factor for the following month.

$$CO_{i-1} = (AP_{i-1} - AMP_{i-1})W_i$$

For example the carry-over from March to April was taken as the amount of surplus or deficit in March multiplied by the weighting factor for April. For the first month of record, carry-over was taken as zero so the effective precipitation was equal to the actual precipitation. Effective precipitation for each month of record for each of the six sub-regions was thus calculated as follows:

$$EP_i = AP_i + CO_{i-1}$$

where: EP_i = effective precipitation for the i^{th} month
AP_i = actual precipitation for the i^{th} month
CO_{i-1} = carry-over from the previous month.

Deficit/Surplus

The next step in the analysis involved the calculation of the deficit or surplus of monthly effective precipitation. This was taken to be the difference between the effective precipitation for the month and the average effective precipitation for that month, over the period of record. This procedure resulted in a time series of monthly deficits and surpluses for each of the six sub-regions. These surpluses and deficits were plotted on bar graphs. Figures 2 and 3 show the graphs for sub-regions 2 and 4. (Hereafter references to "precipitation" refer to "effective precipitation" unless otherwise explicitly noted.)

Inspection of the time series or graphs of surpluses and deficits gives an overview of wet and dry periods, but it is not always possible by merely inspecting this record to decide in which month a drought begins or ends. Consequently a set of criteria had to be established to specify the beginning and ending of a drought.

Drought Criteria

In order to objectively identify periods of drought it was necessary to develop a set of criteria which could be applied to the time series of deficits and surpluses to determine the beginning and ending of a drought. Questions such as: "How long and severe a dry period is required to begin a drought?" and "Once a drought begins what criteria shall be used to determine when it has ended?" had to be addressed. Several possible criteria for determining the beginning and ending of drought were examined and applied to historical droughts in the area. The final criteria were chosen empirically after exploring a number of possibilities and applying them to historical droughts.

The beginning of a drought was specified by two simple and necessary criteria. A drought was deemed to have begun:

i) in the first month of three successive months with a precipitation deficit provided that
ii) in at least one of the three months the deficit was greater than the mean monthly deficit for that month. (The mean monthly deficit was defined as the sum of all the deficits for the given month over the period of record divided by the number of deficits.)

Criteria for determining when a drought had ended were also examined with reference to historical droughts. Again two simple criteria were selected. A drought in progress was deemed to have ended:

i) in the month prior to the month in which the cumulative total of deficits and surpluses from the beginning of the drought became positive
or
ii) in the last month with a deficit prior to a period when at least two of three months had a surplus.

Drought Severity

Dracup et al. (1980) specify three components of drought: duration, magnitude (average water deficiency) and severity (cumulative water deficiency). Duration and severity have been chosen for this study. If desired, magnitude can easily be derived by dividing severity by duration.

Examination of several of the longer, more serious droughts, however, revealed that in some cases the cumulative water deficiency did not truly represent the severity of the drought. This occurred where a month with a large precipitation surplus followed a prolonged period of deficits. Although not sufficient to end the drought by bringing the cumulative water deficit to zero, condition (i), it did significantly reduce the cumulative water deficit thus causing the drought to appear less severe. To more realistically specify severity of droughts, the definition of severity was modified to be "the greatest cumulative water deficit" during a drought. This was also equal to the cumulative water deficit in most cases. For each drought period identified the total duration and severity were calculated. (Table 1 and Table 2 are examples).

Frequency Analysis

The time series of drought severity for each sub-region were analyzed with respect to the frequency of occurrence of observed droughts. These data were in turn used to estimate the severity of drought which one might expect for selected return periods between 2 and 100 years. The observed frequency distribution of drought severity proved to be complex and would be poorly fit by commonly used statistical distributions. Initially, non-parametric analysis of the observed frequency was used to estimate the mean recurrence interval (return period). However, beyond 7-10 years the uncertainty of the non-parametric estimate becomes unacceptably large and other methods had to be used. Classical extreme value analysis could not be used since it is based on series of annual maximum values and the drought events identified in this study had durations of 3-24 months. The method chosen to estimate drought severity for return periods greater than 7 years was the peak-over-threshold (POT) extreme value analysis method. POT analysis could not be used throughout since, in some cases, the minimum return period which could be calculated, using POT, was greater than 5 years. The final estimates of return periods were derived from a combination of non-parametric analysis for the shorter durations (2-7 years) and POT analysis for durations greater than 7 years. Details of the frequency and uncertainty analyses, including theoretical discussions may be found in the complete report. Using the extreme value analysis methods return periods for given drought intensities were calculated and graphed along with the 80% confidence intervals. The return periods for historical droughts may be calculated from these graphs. (Figure 4 and Figure 5).

The complexity of the observed frequency distributions of drought severities in the SSRB presented considerable analysis difficulty. Assumptions of somewhat unknown validity for the model distribution and event independence were necessary. **The user is cautioned that the return periods of extreme values presented here cannot be considered to be statistically valid estimates.** However, the calculated values of return period are self-consistent and correspond with observed frequencies within the associated uncertainty ranges, and should provide useful estimates for planning purposes.

Conclusions

The analysis of meteorological drought in the SSRB has been a difficult and complex undertaking. Due to the complexity of the observed drought distributions and the need to attain some reasonable confidence in the model assumptions, it was necessary to develop a modification to the usual extreme value analysis methods.

This work should be considered as a first step in the analysis of drought events in the SSRB. The analysis has shown that it might be desirable to change the definition of meteorological drought to improve the analysis' utility for particular purposes. This would involve refinements to the criteria for specifying the commencement and termination of drought events. Further work is also desirable in the frequency analysis of drought. Nevertheless, this work has produced a usable analysis of meteorological droughts in the SSRB along with a procedure for estimating mean recurrence intervals (return periods) for droughts of given severities within the sub-regions in the basin.

Table 1: SUB-REGION 2 DROUGHTS

Start	End	Duration (months)	Severity (mm)	Return Period (yrs)	% of Average Precipitation
Oct 1912	Dec 1912	3	20	< 2.0	57%
Mar 1913	May 1913	3	57	< 2.0	31%
Oct 1913	Sep 1914	12	144	14.	67%
Dec 1914	Nov 1915	12	118	4.8	73%
Feb 1916	Apr 1916	3	18	< 2.0	70%
May 1917	Feb 1918	10	90	2.8	77%
Sep 1918	Jul 1919	11	159	31.	59%
Apr 1920	Jul 1920	4	59	2.0	74%
Nov 1920	Jan 1921	3	27	< 2.0	52%
Sep 1922	Feb 1923	6	26	< 2.0	74%
Sep 1923	Sep 1924	13	160	33.	67%
Nov 1925	Mar 1926	5	49	< 2.0	49%
Dec 1927	May 1928	6	69	2.2	51%
Sep 1928	Mar 1929	7	61	2.0	64%
Jun 1929	Oct 1929	5	96	3.2	62%
Jan 1930	Mar 1930	3	26	< 2.0	54%
Nov 1930	Aug 1931	10	109	4.0	68%
Sep 1932	Feb 1933	6	50	< 2.0	64%
Jun 1933	Aug 1933	3	91	2.9	53%
Aug 1934	Nov 1934	4	43	< 2.0	72%
Jul 1936	Nov 1936	5	124	5.9	38%
Mar 1937	Sep 1937	7	136	9.0	60%
Aug 1939	Nov 1939	4	65	2.1	54%
Apr 1940	Sep 1940	6	70	2.2	77%
Mar 1941	Mar 1942	13	187	130.	60%
Jun 1943	Sep 1943	4	83	2.6	62%
Aug 1944	Jul 1945	12	137	10.	66%
Oct 1945	Dec 1945	3	29	< 2.0	50%
Mar 1946	Jul 1946	5	82	2.5	66%
May 1947	Jul 1947	3	76	2.3	58%
May 1948	Oct 1948	6	150	19.	51%
Feb 1952	Jan 1953	12	157	28.	65%
Aug 1953	Dec 1953	5	51	< 2.0	63%
Oct 1954	Dec 1954	3	14	< 2.0	78%
Jun 1955	Aug 1955	3	84	2.7	56%
Apr 1956	Jul 1957	16	168	49.	75%
Jan 1959	Aug 1959	8	122	5.2	64%
Jul 1960	Jan 1961	7	153	23.	38%
Jun 1961	Sep 1961	4	80	2.4	64%
Apr 1962	Jun 1962	3	78	2.4	44%
Sep 1962	Nov 1962	3	31	< 2.0	62%
Jan 1964	Jul 1964	7	104	3.6	63%
Oct 1964	May 1966	20	121	5.2	80%
Apr 1967	Jul 1967	4	96	3.1	52%
Jun 1969	Aug 1969	3	62	2.0	66%

Table1: SUB-REGION 2 DROUGHTS (continued)

Start	End	Duration (months)	Severity (mm)	Return Period (yrs)	% of Average Precipitation
Aug 1970	Oct 1970	3	57	< 2.0	53%
Aug 1971	Nov 1971	4	59	2.0	43%
Aug 1972	Nov 1972	4	67	2.1	49%
Sep 1974	Dec 1974	4	42	< 2.0	54%
Jul 1975	Jan 1976	7	80	2.4	67%
Aug 1976	Jul 1978	24	167	47.	80%
Jul 1979	Sep 1979	3	67	2.2	53%
Mar 1980	Jul 1980	5	105	3.7	55%
Jan 1981	Mar 1981	3	26	< 2.0	55%
Nov 1981	Apr 1982	6	56	< 2.0	52%
Dec 1982	Feb 1983	3	33	< 2.0	42%
Dec 1983	Aug 1984	9	128	6.6	61%
Dec 1984	Mar 1985	4	22	< 2.0	71%
Jun 1985	Feb 1986	9	100	3.4	35%
Oct 1986	Jul 1988	22	266	4257	41%

Table 2: SUB-REGION 4 DROUGHTS

Start	End	Duration (months)	Severity (mm)	Return Period (yrs)	% of Average Precipitation
Sep 1922	Apr 1923	8	65	2.8	59%
Aug 1923	Jul 1924	12	145	39.	64%
Dec 1927	May 1928	6	62	2.7	56%
Aug 1928	Oct 1929	15	228	150.	56%
Jan 1930	Aug 1930	8	74	3.6	76%
Nov 1930	Nov 1931	13	126	25.	77%
Dec 1932	Jul 1933	8	107	14.	62%
Jan 1934	Dec 1934	12	123	23.	70%
Sep 1935	Dec 1935	4	40	< 2.0	54%
Apr 1936	Dec 1936	9	129	27.	64%
Mar 1937	Dec 1937	10	183	80.	53%
Aug 1939	Nov 1939	4	69	3.0	42%
Jun 1943	Sep 1943	4	87	5.6	58%
Dec 1943	Feb 1944	3	27	< 2.0	54%
Sep 1944	Dec 1944	4	46	< 2.0	49%
May 1945	Aug 1945	4	101	11.	58%
Mar 1946	Jun 1946	4	69	3.0	62%
Aug 1948	Oct 1948	3	67	2.9	26%
Jan 1949	Sep 1949	9	82	4.5	76%
Oct 1953	Mar 1954	6	28	< 2.0	76%
Oct 1954	Feb 1955	5	26	< 2.0	66%
Aug 1955	Oct 1955	3	42	< 2.0	47%
Apr 1956	Sep 1956	6	66	2.8	78%
Mar 1958	Jun 1958	4	105	13.	37%
Jan 1959	Aug 1959	8	56	2.2	83%
Jun 1961	Feb 1962	9	154	47.	52%
Nov 1962	May 1963	7	44	< 2.0	74%
Sep 1963	Jan 1964	5	42	< 2.0	61%
Jun 1964	Nov 1964	6	62	2.6	84%
May 1967	Aug 1967	4	155	49.	36%
Jan 1968	Jul 1968	7	108	15.	61%
Aug 1970	Nov 1970	4	50	2.1	58%
Mar 1971	May 1971	3	47	2.0	46%
Aug 1971	Dec 1971	5	65	2.7	53%
Nov 1972	Oct 1973	12	121	23.	72%
Oct 1974	Feb 1975	5	52	2.1	46%
Aug 1976	Apr 1977	9	125	25.	41%
Aug 1977	Mar 1978	8	59	2.4	67%
Jun 1978	Aug 1978	3	56	2.3	68%
Nov 1979	May 1980	7	72	3.3	54%
Feb 1981	May 1981	4	46	< 2.0	56%
Nov 1982	Feb 1983	4	23	< 2.0	67%
Dec 1983	Aug 1984	9	90	6.6	73%
Jun 1985	Aug 1985	3	88	6.0	57%
Nov 1985	Apr 1986	6	42	<2.0	40%
Sep 1987	??	(12)	(158)	(51)	(45%)

FIGURE I

SOUTH SASKATCHEWAN RIVER BASIN
SUB-REGIONS

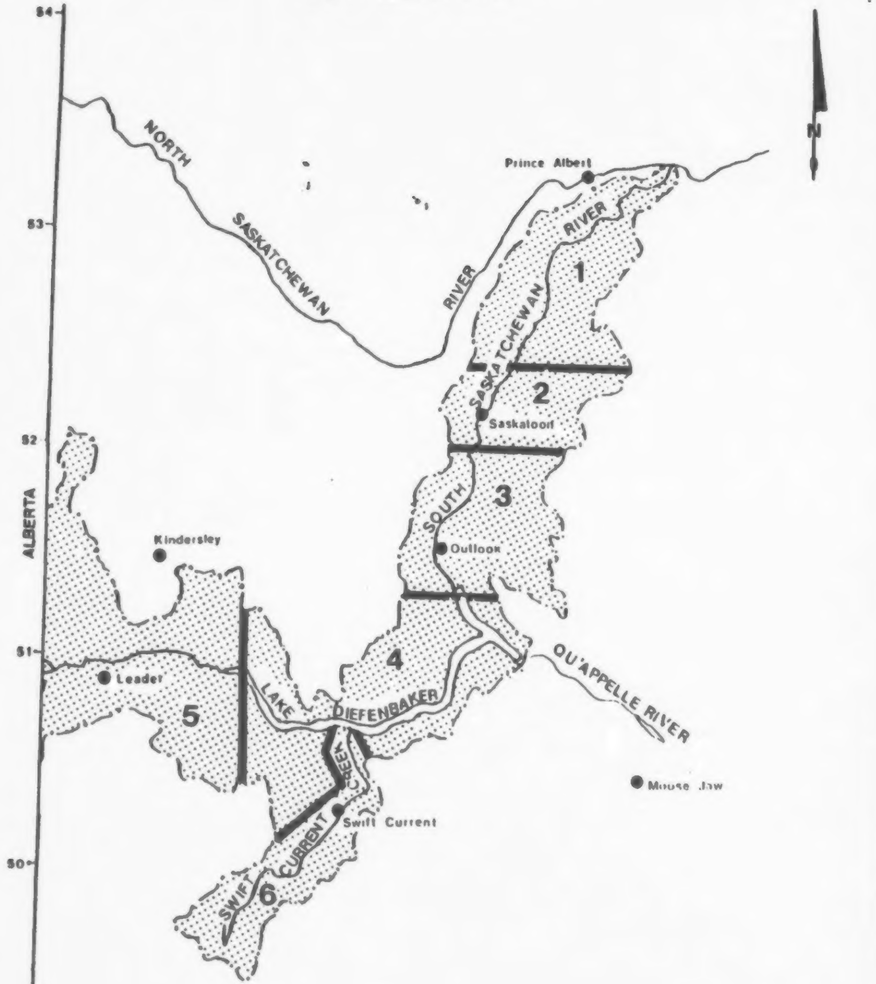

54
53
52
51
50
49
NORTH SASKATCHEWAN RIVER
N
Prince Albert
RIVER
1
SASKATCHEWAN
2
Saskatoon
SOUTH
3
Outlook
ALBERTA
Kindersley
4
QU'APPELLE RIVER
Leader
5
LAKE DIEFENBAKER
CREEK
Moose Jaw
Swift Current
SWIFT CURRENT
6
SASKATCHEWAN
110
109
108
107
106
105
104
UNITED STATES

FIGURE 2

Effective Precipitation
Sub-region 2

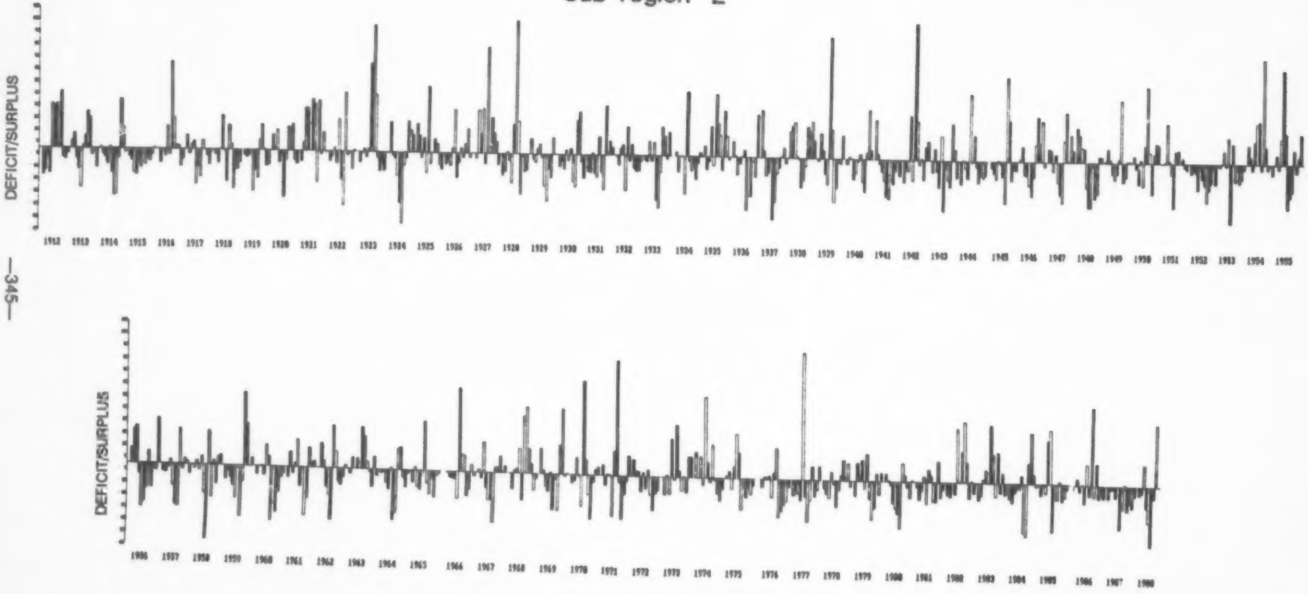


FIGURE 3

Effective Precipitation
Sub-region 4

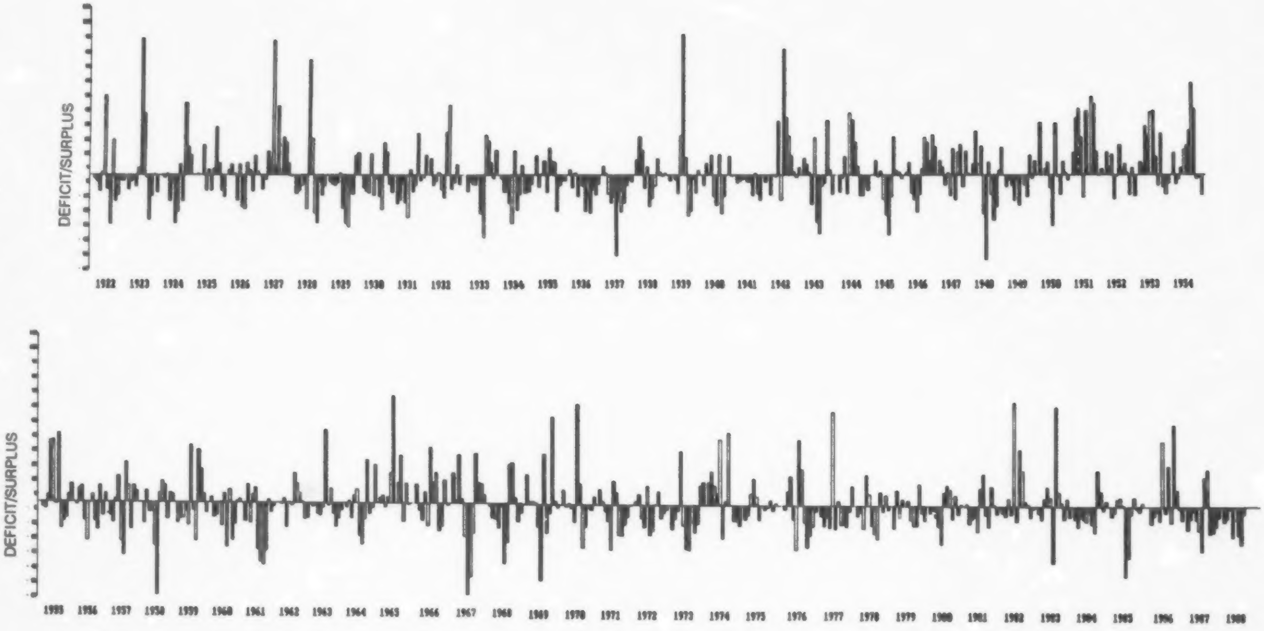


FIGURE 4

Sub-region 2 Drought Severity vs. Duration

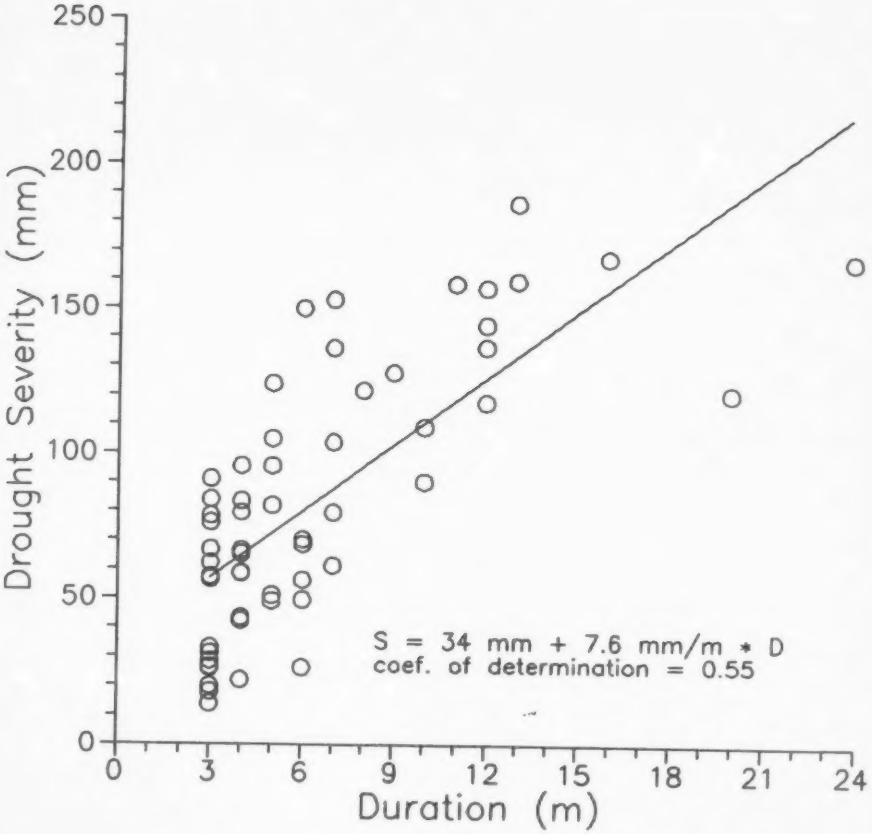
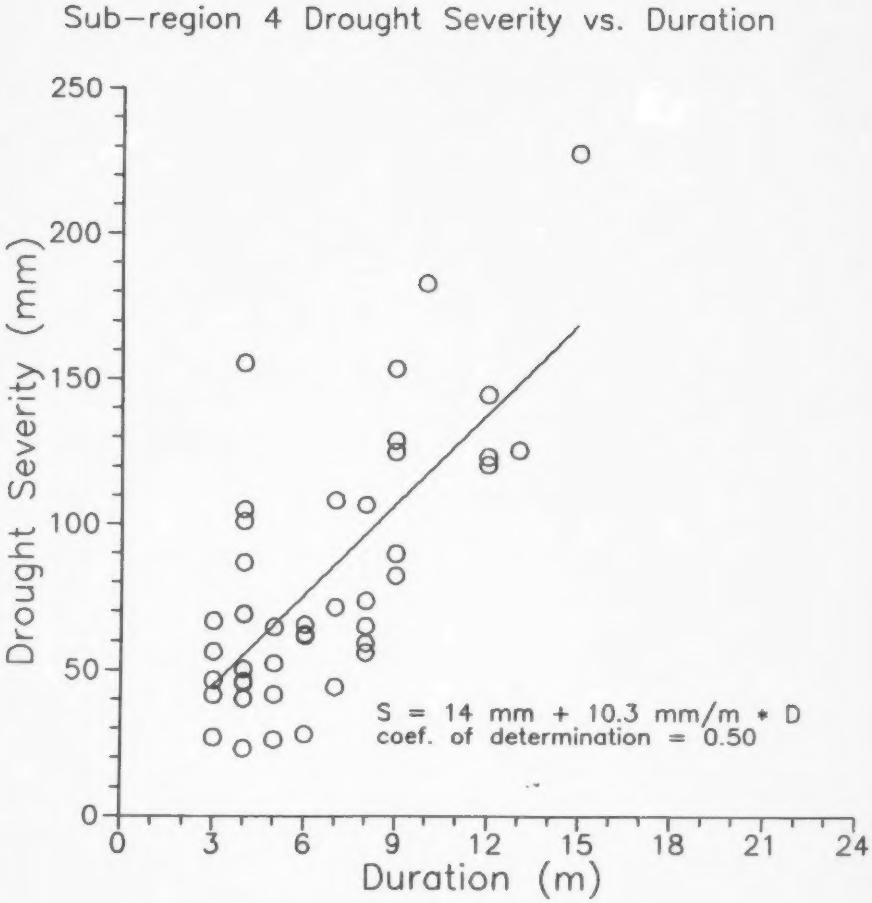


FIGURE 5


Sub-region 4 Drought Severity vs. Duration
Drought Severity (mm)
250
200
150
100
50
0
0
3
6
9
12
15
18
21
24
Duration (m)
S = 14 mm + 10.3 mm/m * D
coef. of determination = 0.50

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